REPORT NO. SM-43105

EVALUATION OF MARAGING STEEL FOR APPLICATION
TO SPACE LAUNCH VEHICLES
CONTRACT NAS 7-214   WOO-PR-63-172

Final Report

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ABSTRACT

An investigation was undertaken to evaluate mechanical and metallurgical properties of 3/4-in thick airmelted 18Ni-7Co-5Mo alloy plate and of welds deposited in the alloy. Plates from three heats were included in the study. Welds were made under a wide range of conditions and with a variety of filler wire compositions.

The evaluations included determinations of the effects of aging heat treatment on the mechanical properties of welds and plate. Uniaxial tensile, plane strain fracture toughness (employing partial thickness crack specimens), hardness, and sustained load properties were studied. The development of a sub-size plane strain fracture toughness specimen was also undertaken.

Metallurgical investigations included the use of novel electron fractographic methods. Such methods supplemented with electron diffraction and x-ray microprobe analysis techniques were employed for phase identification.

The principal results of this investigation may be summarized as follows:

1. Significant differences in the tensile and fracture toughness properties of the three airmelted 18Ni-7Co-5Mo plate heats were observed despite similar chemical compositions.

2. A small partial thickness crack specimen was developed which produced fracture toughness results agreeing closely with results obtained from more conventional larger specimens.

3. Tensile efficiency of weld joints generally exceeded 90 per cent after most aging treatments and approached 100 per cent after some.

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ABSTRACT (Cont'd.)

4. Welds exhibited inferior fracture toughness properties compared to plate.
    Fracture toughness was found to be relatively independent of welding
    procedure, gross chemical composition, and post weld heat treatment.

5. Titanium nitride was identified as a prevalent constituent on the fracture
    surfaces of weldmetal. The phase was found to be present in the form of
    semi-continuous networks. This phase appears to be the cause of degraded
    weldmetal toughness and the occasional occurrence of poor heat-affected
    zone toughness. Titanium nitride was also found to be prevalent in plate,
    however, not in the form of semi-continuous networks.

6. Practical welding problems were encountered in applying laboratory welding
    procedures to production prototype conditions.

7. Radiographic inspection of welds does not appear to be capable of detect-
    ing damaging crack-like defects.

8. Plate and welds both exhibited some slow crack growth susceptibility
    when subjected to sustained loads in various liquid environments,
    However, welds appear to be far more susceptible.

The results of this investigation demonstrate that several problem areas
must be subjected to further study.

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I.   # INTRODUCTION

This program was conducted under the sponsorship of NASA, Space
Vehicle Research and Technology. The purpose was to evaluate the
properties of airmelted 18Ni-7Co-5Mo maraging steel plate and welds,
and to investigate the associated processing techniques for potential
application to space launch vehicle construction. Welding was
performed both by Douglas Aircraft Co., and Newport News Ship-
building and Dry Dock Co., (acting as a subcontractor)to determine
the reproducibility of welding procedures.

During the last two years, Douglas Aircraft Co. has been active in
company sponsored research and development programs to evaluate 3/4-
inch thick airmelted 18Ni-7Co-5Mo plate. The programs were under-
taken to determine the properties and fabricability of the alloy,
and to define potential problems areas.

Under the current NASA contract, 3/4-inch thick plate from two new
heats of airmelted 18Ni-7Co-5Mo steel was evaluated and the results
related to those previously obtained.

Included in the present program were evaluations of the effects of
aging treatment on uniaxial tensile properties and fracture tough-
ness of both plate and welds. Welds were deposited in plate from
one of the two new heats using the inert-gas shielded metal arc
technique, using filler wire selected during the earlier company-
sponsored program. Sustained-load behavior of plate and weldments
exposed to various environments was also investigated.

Fracture toughness results generated using subsize partial thickness

I.   <u>INTRODUCTION</u> (Cont'd.)

crack (PTC) specimens were compared to those obtained with large PTC specimens. The results demonstrated the suitability of the subsize specimen.

Metallurgical evaluations were undertaken employing novel electron fractographic techniques. These studies resulted in the tentative identification of titanium nitride as the cause of inferior weld-metal fracture toughness.

The first progress report (Ref. 23) presented data on Heat I and preliminary data on Heat A. Included in the report was information on chemistry, metallographic inspection, dimensional and soundness examination, uniaxial tensile properties, fracture toughness and plane-strain toughness characteristics.

Progress Report No. 2 (Reference 24) presented the remainder of the data on Heat A, preliminary data on Heat B, and initial inspection results on the weld wire. Information on Heat A included examination of fracture surfaces of the 24" x 3" x 3/4" partial thickness crack (PTC) coupons by use of the electron microscope. Heat B results included data on uniaxial tensile properties, fracture toughness, chemical analysis and metallographic examination.

This final report includes the data presented previously in Progress Reports I and 2 and presents all new data, a substantial portion of which pertains to weld evaluations.

The results of this study indicate that several problem areas

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I.   <u>INTRODUCTION</u> (Cont'd.)

require further study. Among the more important are those related
to: a) banding and the prevalence of titanium nitride inclusions in
plate, b) the effects of titanium nitride inclusions in weldmetal,
c) control and reproducibility of the aging response of plate with
respect to strength and fracture toughness and, d) environmental
influence on fracture, especially with respect to welds.

2.   ## EVALUATION OF PLATE PROPERTIES

Data are presented in this section describing the mechanical pro-
perties of plate from three different heats of 18Ni-7Co-5Mo alloy
steel. Tensile, fracture toughness, hardness, and plate quality
properties are described. Effects of aging treatment and specimen
orientation (with respect to rolling direction) are comprehensively
treated.

2.1   ### Plate Properties

Plate from three different heats of air melted 18Ni-7Co-5Mo steel
was evaluated. The three heats were produced by U.S. Steel Corp-
oration by electric furnace, air melting techniques. They are
referred to throughout this report as Heats I, A, and B.

Heat I plate was part of a twenty-two ton melt donated by U.S. Steel
Corporation for a previous company sponsored program (References 5
and 6). Two plates, approximately 240-in. x 110-in. x 3/4-in. were
used in this evaluation.

Heat A material was received as one air melted plate approximately
84-in. x 60-in. x 3/4-in.

Heat B material was procured in accordance with Douglas' tentative
specification DMS 1835 (Appendix I). The material was received in
the form of two air melted plates, hereafter designated plates I
and 2. One plate was 348-in. x 120-in. x 3/4-in. and the other was
300-in. x 120-in. x 3/4-in.

2.1   Plate Properties (Cont'd.)

Table I presents the chemical compositions of the three heats.
Heat I chemistry was determined by the supplier and the chemistries
of Heats A and B were determined by the supplier, Douglas and
Newport News. The analyses conform quite closely to the requirements
in Appendix I. The titanium contents were purposely selected for
Heats A and B to bracket the nominal range for the 18Ni-7Co-5Mo
alloy. Heat I contains the nominal amount (0.46), Heat A is near
the lower limit (0.40) and Heat B is near the upper limit (0.55).
Also in Heat B the cobalt and molybdenum are at the upper limits
and aluminum is slightly higher than DMS 1583 specifies.

2.2   Plate Inspection Procedures

The plates were received from the mill at Newport News Shipbuilding
and Dry Dock Co. wrapped in rust inhibiting paper. All plates were
visually inspected and any defects such as pits and inclusions were
recorded. The plates were then ultrasonically inspected for thick-
ness uniformity and soundness. Pulse-echo techniques were employed
for test of soundness using full saturation back reflection and a
rejection criteria of 10 percent loss of back reflection. Inspec-
tion points were located on a six inch grid intersect.

2.3   Plate Layout

Figure I through 5 schematically illustrate the plate layouts and
specimen coding used in this program. Plasma arc cutting and
abrasive sawing were used to rough cut the specimen blanks prior
to finish machining. Liberal allowances were provided to permit

TABLE I

CHEMICAL COMPOSITIONS OF HEATS I, A, AND B AIRMELTED 18Ni-7Co-5Mo 3/4"-THICK PLATE

CHEMICAL COMPOSITION, WEIGHT PERCENT

__PLATE__

HEAT CODE	U.S.S. HEAT NO.	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Al	Ti	Co	B	Zr	N₂	SOURCE
I	X13371	0.02	0.04	0.004	0.009	0.08	0.05	17.83	0.01	4.70	0.11	0.46	7.41	NA	NA	NA	U.S.S. Douglas
A	X14359	0.02	0.03	0.005	0.005	0.09	0.11	17.73	0.01	4.80	0.07	0.39	7.40	0.004	NA	0.005	U.S.S.
A	X14359	0.01	0.06	0.002	0.006	0.07	NA	17.35	NA	4.79	NA	0.41	7.81	NA	0.01	NA	Douglas
A	14359	0.02	0.06	0.009	0.004	0.08	0.05	17.83	NA	4.68	0.15	0.39	6.98	0.0004	0.0022	0.006	Newport News
B	52911	0.02	0.02	0.008	0.009	0.03	0.14	18.11	NA	4.90	0.09	0.58	NA	0.003	0.01	NA	U.S.S. LADLE CHEMISTRY
B	52911	0.02	0.02	0.004	0.009	0.03	0.15	18.09	NA	4.90	0.08	0.49	8.07	NA	NA	CHECK CHEMISTRY	U.S.S.
B	52911	0.01	0.007	0.005	0.013	NIL	NA	17.90*	NA	5.0*	0.18	0.58 / 0.54*	8.38*	NA	NA	0.009	Douglas
B	52911	0.02	0.035	0.006	0.010	0.06	0.07	17.67	NA	4.85	0.16	0.56	7.36	0.01	NIL	NA	Newport News

* Spectrographic Analysis

NA No Analysis

2.3   <u>Plate Layout</u> (Cont'd.)

the removal of all material affected by the heat of plasma arc
cutting.

2.4   <u>Test Specimen Types and Testing</u>

Uniaxial tensile data for parent plate were obtained for the three
heats using standard ASTM 0.505-in. diameter specimens illustrated
in Figure 6. Fracture toughness evaluations on Heat I, parent plate
and weldments, were conducted using 48-in. x 4-in. x 3/4-in. partial
thickness crack (PTC) specimens shown in Figure 7. Heat A parent
plate fracture toughness properties were investigated by using the
24-in. x 3-in x 3/4-in. PTC specimens, Figure 8. Heat B parent
plate and weldment fracture toughness evaluation also employed the
use of the 24-in PTC as well as a slab-type 8-in, PTC coupon
Figure 9. Uniaxial tensile data on weldments were obtained with
0.505-in. diameter specimens for across-the-joint tests Subsize
0.250-in. diameter specimens, (Figure 10) were used for all-weld-
metal tensile evaluation described in later sections. Sustained
load evaluations employed the 24-in and the 8-in PTC coupons.

Load rates were maintained at approximately 100,000 PSI per minute
for both tensile and fracture toughness testing. All tests that
were conducted in the ambient atmosphere were accomplished at
temperatures ranging from 70 to $80^{\circ}F$, and with relative humidity from
about 25 to 65%..

LAYOUT, HEAT-1, PLATE NO. 1

FIGURE 1

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LAYOUT, HEAT-I, PLATE NO. 2

FIGURE 2

240"

108"

ROLLING DIRECTION

FIGURE 3

LAYOUT, HEAT-B, PLATE NO. 1

ROLLING DIR.

348"

120"

106¼"

P41	24"
P41 P42	4.1.1.4
P42	

G 6" 6"

P52	24"
P52 P53	4.1.3.2
P53	

B

P110 / P110 — P45 / P45 — P45 / P44 — P44 / P54 — P54 / 31W8 31W8 / 31W7 / 31W7

E 3" 3"

P14 / P13 / P13 P46 / P46 P56 / P56 P55 / P55 P55

4.1.1.4 4.1.1.3 3.505" P55

1C P31 P32 P33 4.1.2
L P34 P35 P36
P61-P612 4.1.3.3 4.1.3.3 P613-P624

8-LONG .505" TEN.

8-TRANS. .505" TEN.

4.3.1 4.1.2 19¼" 9" 9" 6"

5W13
5W12 4.2.1.5 DAC
5W11 N.N.
5W10 DAC 13"
5W9 N.N. 13"

4.1.2 8-TRANSV .505" TEN.
4.1.2 8-LONG 505" TEN.

6W8 DAC 13" 52"
6W7 AGE DAC 13"

P51 4.1.3.2 P51 24" 9" J
H SURPLUS

6W6 DAC 13"
6W5 AGE DAC 13"
6W4 4.2.1.6 N.N. 13"
6W3 AGE N.N. 13"
6W2 N.N. 13"
6W1 AGE N.N. 13" 52"

AGE 13"
AGE DAC 13"
AGE 13"
AGE DAC 13"

5W5
5W6 4.2.1.5
5W7
5W8 52"

5W1
5W2 DAC
5W3 N.N.
5W4 DAC

4.2.1.6 N.N.

FIGURE 4

$129\frac{1}{2}$"

LAYOUT, HEAT-B, PLATE NO. 2

FIGURE 5

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UNIAXIAL TENSILE TEST SPECIMEN
0.505-IN. DIAMETER ROUND BAR

FIGURE 6

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PARTIAL THICKNESS CRACK FRACTURE TOUGHNESS
SPECIMEN – 48" X 4" X 3/4"

FIGURE 7

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PARTIAL THICKNESS CRACK FRACTURE TOUGHNESS
SPECIMEN – 24" X 3" X 3/4"

FIGURE 8

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8'' X 11/16'' X 5/16'' PARTIAL THICKNESS CRACK FRACTURE TOUGHNESS SPECIMEN

FIGURE 9

UNIAXIAL TENSILE TEST SPECIMEN
0.250-IN. DIAMETER ROUND BAR

3/8 D

1/8" R TYP

3/8"-24
NF2 THDS

19/64"

.250"

1-1/4"

.250"

.250"

19/64"

3-1/4"

1/2" R
TYP

1/2"

CHAM. 45" × .031
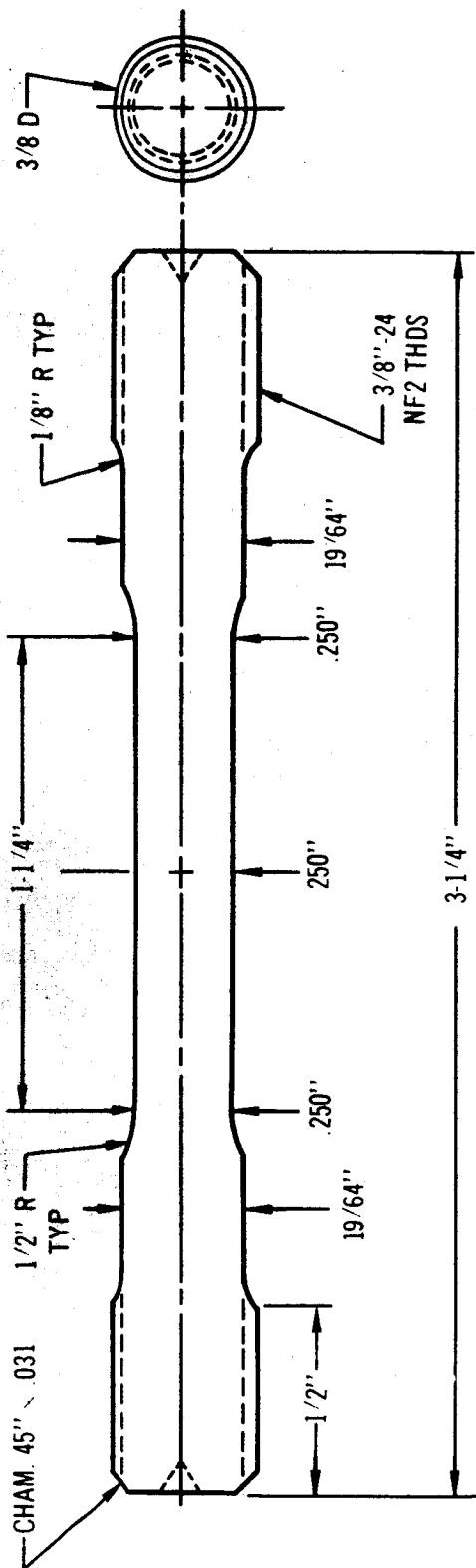
FIGURE 10

2.5   Heat Treatment Procedures

All aging heat treatments were performed on as-machined specimens
taken from the as-received, mill-annealed, plate. The mill anneal
was performed at $1500^\circ F$ for 1 hour followed by air cooling. All
specimens were subsequently aged at temperatures ranging from 875
to $1000^\circ F$ in convective air furnaces. Specimens were batch loaded,
when possible, into a hot furnace which had been previously heated
to the desired aging temperature. The specimens were then allowed
to come to thermal equilibrium with the furnace before the nominal
aging period was started. Temperature was monitored by means of
independent thermocouples located at different positions within the
furnace, and by thermocouples located on the test parts.

The attainment of thermal equilibrium took from 30 to 45 minutes for
0.250 and 0.505-inch diameter round bar and 8-inch PTC specimens.
Approximately 1 1/2 hours was required for the 3/4" thick fracture
toughness specimens. Once thermal equilibrium was achieved, temper-
ature control was maintained to within $\pm 7^\circ F$. The aging times
reported are those recorded subsequent to the attainment of thermal
equilibrium. All specimens were cooled to room temperature in
ambient still air following the aging heat treatment.

2.6   Preparation of Partial-Thickness Crack Specimens

Partial thickness cracks were induced in the fracture toughness
specimens by means of a flexural fatigue procedure similar to that
described in Douglas Laboratory Procedure, DLP 13.822 presented in
Appendix III. The DLP presents the procedure used for sheet material,

2.6   Preparation of Partial-Thickness Specimens

rather than plate. However, the general procedures are identical

for plate, except that the fixtures are more massive.

Approximately 5,000 to 10,000 cycles were required to initiate a

visible crack, and up to 50,000 cycles were needed to achieve the

desired crack size. Flexure was performed at maximum fiber stresses

ranging from 120,000 to 160,000 psi   (flexed in aged condition).

2.7   Results and Discussion

2.7.1   Dimensional, Soundness and Hardness Inspection
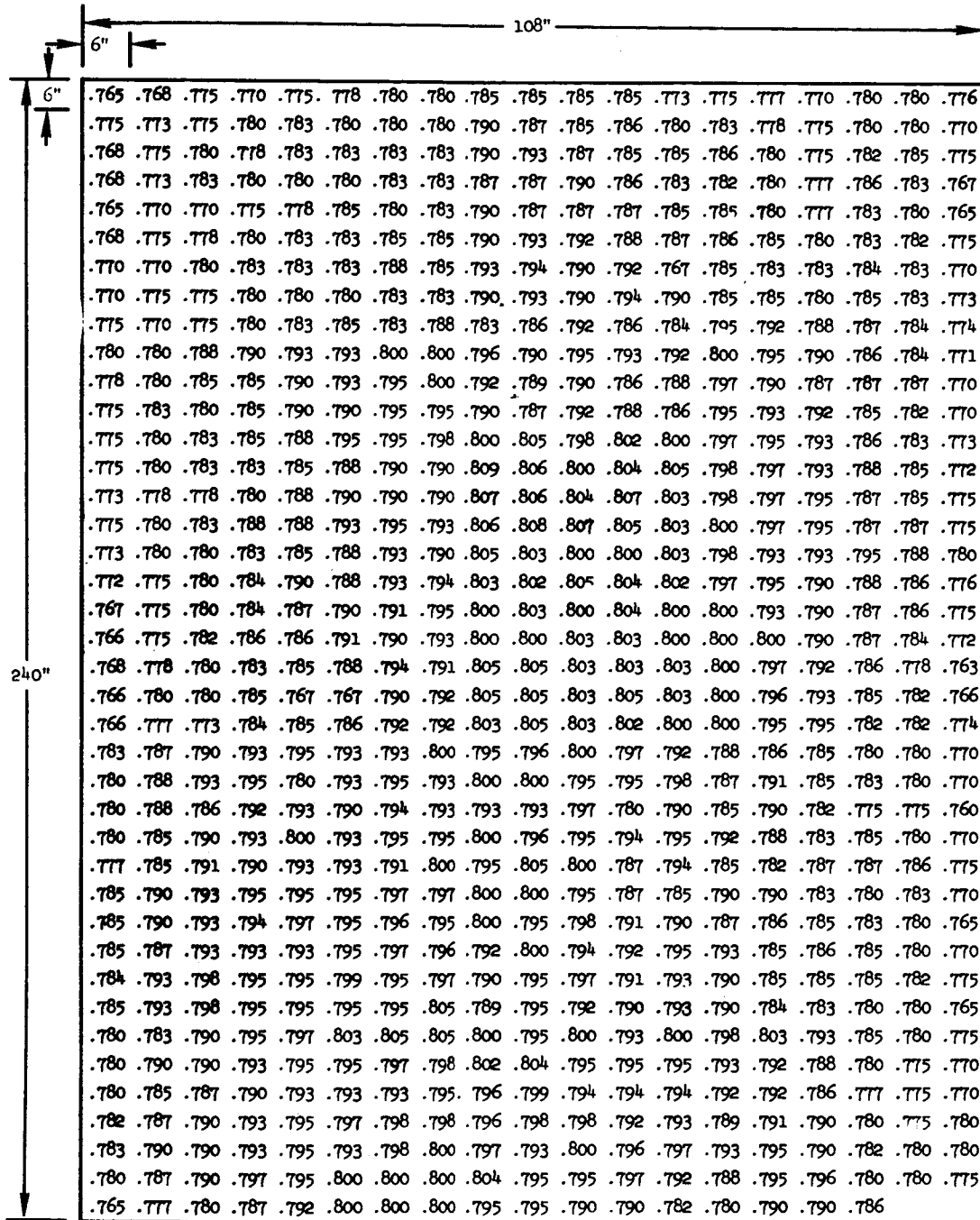
Ultrasonic inspection failed to indicate any defect which could be

rejected based upon DMS 1835, in either Heat 1, A or B Plate.

Thickness transverse data are tabulated in Tables II thru VI.   The

tolerances for Heat 1 plates exceed the maximum specified in AMS 2252

(plus 0.044, minus 0.010-in.) ranging between 0.750-in. plus 0.059,

minus zero for plate 1 and plus 0.088, minus zero for plate 2.

Heat A plate thickness ranges between 0.750-in. plus 0.044, minus

zero.   The latter bordered on the upper limits of AMS 2252 require-

ments. Heat B plate thickness ranged between 0.750-in. plus 0.150,

minus zero. However, the excessive thickness was located in one

region only, and the rest of the points were nominally 0.750-in

plus 0.050-in, minus zero. Because of the experimental nature of

this program the material was accepted. However, under other con-

ditions the heat might have been rejected because the plate thick-

ness tolerances exceeded the limits of AMS 2252.

TABLE II

ULTRASONIC THICKNESS TRAVERSE FOR HEAT-1, PLATE 1

108"

6"

6"

240"

.765	.768	.775	.770	.775.	.778	.780	.780	.785	.785	.785	.785	.773	.775	.777	.770	.780	.780	.776
.775	.773	.775	.780	.783	.780	.780	.780	.790	.787	.785	.786	.780	.783	.778	.775	.780	.780	.770
.768	.775	.780	.778	.783	.783	.783	.783	.790	.793	.787	.785	.785	.786	.780	.775	.782	.785	.775
.768	.773	.783	.780	.780	.780	.783	.783	.787	.787	.790	.786	.783	.782	.780	.777	.786	.783	.767
.765	.770	.770	.775	.778	.785	.780	.783	.790	.787	.787	.787	.785	.785	.780	.777	.783	.780	.765
.768	.775	.778	.780	.783	.783	.785	.785	.790	.793	.792	.788	.787	.786	.785	.780	.783	.782	.775
.770	.770	.780	.783	.783	.783	.788	.785	.793	.794	.790	.792	.767	.785	.783	.783	.784	.783	.770
.770	.775	.775	.780	.780	.780	.783	.783	.790	.793	.790	.794	.790	.785	.785	.780	.785	.783	.773
.775	.770	.775	.780	.783	.785	.783	.788	.783	.786	.792	.786	.784	.795	.792	.788	.787	.784	.774
.780	.780	.788	.790	.793	.793	.800	.800	.796	.790	.795	.793	.792	.800	.795	.790	.786	.784	.771
.778	.780	.785	.785	.790	.793	.795	.800	.792	.789	.790	.786	.788	.797	.790	.787	.787	.787	.770
.775	.783	.780	.785	.790	.790	.795	.795	.790	.787	.792	.788	.786	.795	.793	.792	.785	.782	.770
.775	.780	.783	.785	.788	.795	.795	.798	.800	.805	.798	.802	.800	.797	.795	.793	.786	.783	.773
.775	.780	.783	.783	.785	.788	.790	.790	.809	.806	.800	.804	.805	.798	.797	.793	.788	.785	.772
.773	.778	.778	.780	.788	.790	.790	.790	.807	.806	.804	.807	.803	.798	.797	.795	.787	.785	.775
.775	.780	.783	.788	.788	.793	.795	.793	.806	.808	.807	.805	.803	.800	.797	.795	.787	.787	.775
.773	.780	.780	.783	.785	.788	.793	.790	.805	.803	.800	.800	.803	.798	.793	.793	.795	.788	.780
.772	.775	.780	.784	.790	.788	.793	.794	.803	.802	.805	.804	.802	.797	.795	.790	.788	.786	.776
.767	.775	.780	.784	.787	.790	.791	.795	.800	.803	.800	.804	.800	.800	.793	.790	.787	.786	.775
.766	.775	.782	.786	.786	.791	.790	.793	.800	.800	.803	.803	.800	.800	.800	.790	.787	.784	.772
.768	.778	.780	.783	.785	.788	.794	.791	.805	.805	.803	.803	.803	.800	.797	.792	.786	.778	.763
.766	.780	.780	.785	.767	.767	.790	.792	.805	.805	.803	.805	.803	.800	.796	.793	.785	.782	.766
.766	.777	.773	.784	.785	.786	.792	.792	.803	.805	.803	.802	.800	.800	.795	.795	.782	.782	.774
.783	.787	.790	.793	.795	.793	.793	.800	.795	.796	.800	.797	.792	.788	.786	.785	.780	.780	.770
.780	.788	.793	.795	.780	.793	.795	.793	.800	.800	.795	.795	.798	.787	.791	.785	.783	.780	.770
.780	.788	.786	.792	.793	.790	.794	.793	.793	.793	.797	.780	.790	.785	.790	.782	.775	.775	.760
.780	.785	.790	.793	.800	.793	.795	.795	.800	.796	.795	.794	.795	.792	.788	.783	.785	.780	.770
.777	.785	.791	.790	.793	.793	.791	.800	.795	.805	.800	.787	.794	.785	.782	.787	.787	.786	.775
.785	.790	.793	.795	.795	.795	.797	.797	.800	.800	.795	.787	.785	.790	.790	.783	.780	.783	.770
.785	.790	.793	.794	.797	.795	.796	.795	.800	.795	.798	.791	.790	.787	.786	.785	.783	.780	.765
.785	.787	.793	.793	.793	.795	.797	.796	.792	.800	.794	.792	.795	.793	.785	.786	.785	.780	.770
.784	.793	.798	.795	.795	.799	.795	.797	.790	.795	.797	.791	.793	.790	.785	.785	.785	.782	.775
.785	.793	.798	.795	.795	.795	.795	.805	.789	.795	.792	.790	.793	.790	.784	.783	.780	.780	.765
.780	.783	.790	.795	.797	.803	.805	.805	.800	.795	.800	.793	.800	.798	.803	.793	.785	.780	.775
.780	.790	.790	.793	.795	.795	.797	.798	.802	.804	.795	.795	.795	.793	.792	.788	.780	.775	.770
.780	.785	.787	.790	.793	.793	.793	.795.	.796	.799	.794	.794	.794	.792	.792	.786	.777	.775	.770
.782	.787	.790	.793	.795	.797	.798	.798	.796	.798	.798	.792	.793	.789	.791	.790	.780	.775	.780
.783	.790	.790	.793	.795	.793	.798	.800	.797	.793	.800	.796	.797	.793	.795	.790	.782	.780	.780
.780	.787	.790	.797	.795	.800	.800	.800	.804	.795	.795	.797	.792	.788	.795	.796	.780	.780	.775
.765	.777	.780	.787	.792	.800	.800	.800	.795	.795	.790	.790	.782	.780	.790	.790	.786		

20
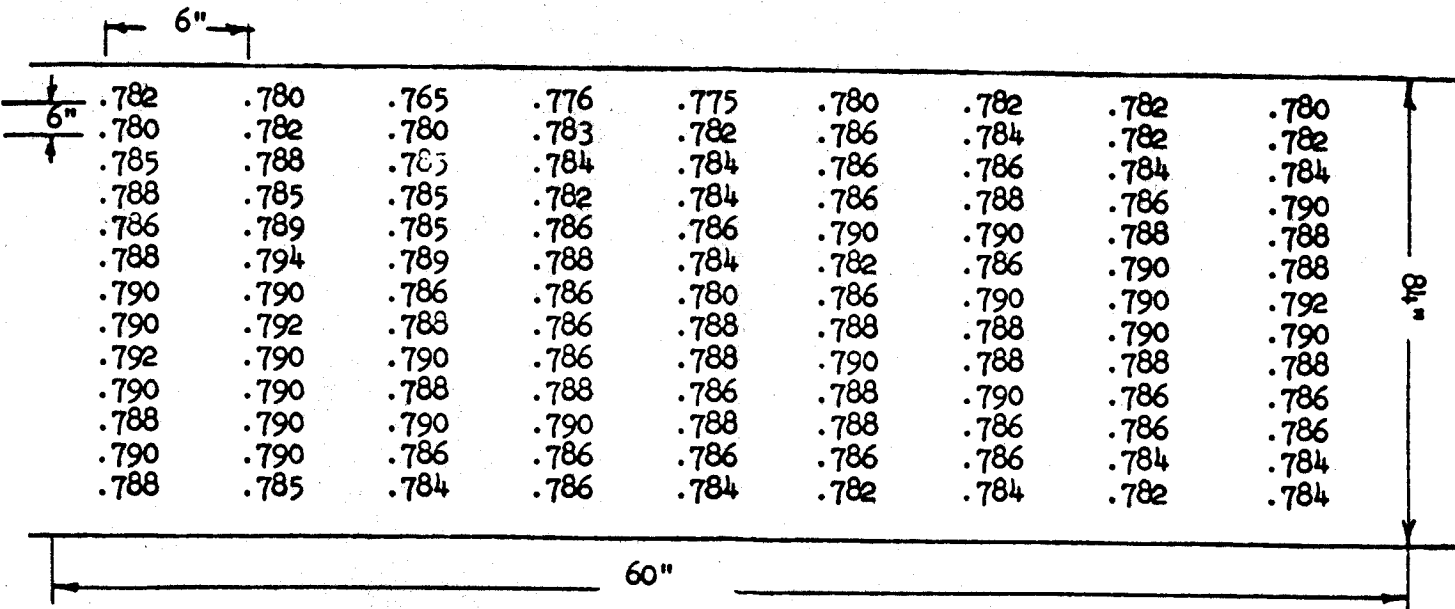
TABLE III

ULTRASONIC THICKNESS TRAVERSE FOR HEAT 1 – PLATE 2

112" (width), 6" offset; 6" and 240" (left side)

.795	.800	.803	.805	.805	.805	.805	.805	.805	.805	.805	.803	.803	.800	.798	.790	.803	.795	.780
.795	.800	.805	.805	.808	.810	.810	.810	.810	.810	.810	.805	.805	.803	.800	.793	.805	.795	.785
.795	.803	.810	.810	.813	.815	.815	.815	.805	.805	.805	.803	.798	.795	.800	.800	.808	.800	.788
.803	.808	.810	.813	.813	.815	.815	.185	.808	.818	.818	.815	.815	.810	.810	.808	.813	.805	.790
.803	.810	.808	.818	.818	.818	.818	.818	.825	.825	.825	.818	.815	.813	.810	.803	.815	.803	.793
.803	.805	.810	.815	.818	.818	.820	.820	.825	.825	.825	.823	.818	.815	.815	.810	.815	.805	.795
.805	.808	.810	.818	.818	.818	.820	.820	.825	.825	.825	.825	.820	.815	.818	.808	.815	.805	.800
.800	.803	.805	.813	.818	.820	.825	.820	.825	.825	.825	.823	.818	.815	.818	.810	.815	.810	.795
.803	.788	.813	.818	.818	.818	.820	.820	.830	.830	.825	.825	.820	.815	.813	.805	.818	.805	.793
.803	.805	.810	.813	.818	.818	.818	.818	.825	.825	.825	.823	.820	.820	.813	.808	.818	.805	.795
.803	.813	.815	.813	.825	.823	.823	.820	.830	.825	.823	.820	.825	.820	.815	.813	.818	.808	.795
.803	.808	.810	.820	.820	.823	.825	.823	.830	.830	.830	.825	.823	.820	.813	.813	.818	.810	.800
.808	.810	.815	.818	.820	.823	.823	.823	.835	.833	.830	.833	.823	.820	.815	.810	.818	.810	.795
.805	.808	.813	.820	.818	.820	.823	.823	.828	.825	.825	.828	.823	.818	.815	.810	.815	.805	.795
.805	.810	.813	.818	.820	.828	.825	.828	.833	.835	.830	.830	.825	.820	.815	.815	.820	.810	.803
.805	.813	.815	.825	.825	.828	.830	.833	.838	.838	.838	.833	.828	.828	.823	.815	.823	.813	.803
.805	.810	.818	.820	.823	.823	.825	.825	.833	.835	.835	.833	.828	.825	.815	.813	.820	.810	.803
.803	.808	.810	.820	.818	.825	.825	.825	.830	.830	.825	.828	.825	.825	.820	.810	.820	.810	.800
.808	.810	.815	.825	.823	.828	.815	.830	.835	.838	.833	.833	.828	.823	.823	.815	.825	.810	.800
.808	.813	.820	.823	.825	.825	.835	.828	.835	.838	.835	.835	.830	.823	.820	.818	.823	.818	.803
.810	.815	.815	.820	.825	.828	.828	.828	.833	.835	.833	.830	.825	.828	.820	.815	.820	.815	.805
.805	.805	.810	.815	.818	.820	.820	.823	.830	.828	.825	.825	.820	.818	.818	.810	.820	.810	.795
.798	.803	.805	.806	.808	.813	.813	.813	.818	.818	.818	.815	.810	.810	.805	.805	.813	.800	.788
.795	.800	.800	.808	.808	.810	.810	.810	.818	.818	.818	.815	.813	.808	.805	.803	.810	.800	.785
.793	.798	.803	.805	.805	.810	.805	.808	.810	.815	.813	.810	.808	.805	.803	.800	.803	.795	.780
.790	.793	.798	.800	.803	.803	.803	.803	.805	.808	.810	.810	.808	.803	.800	.795	.803	.793	.780
.788	.790	.790	.798	.798	.803	.800	.800	.805	.805	.808	.808	.805	.803	.800	.798	.800	.790	.775
.785	.790	.793	.795	.795	.798	.800	.800	.800	.803	.805	.795	.800	.795	.795	.790	.798	.788	.778
.785	.790	.790	.793	.795	.795	.795	.798	.810	.800	.800	.800	.795	.793	.790	.790	.795	.788	.775
.783	.788	.790	.793	.795	.795	.795	.795	.795	.795	.793	.795	.793	.790	.788	.785	.793	.785	.775
.783	.788	.790	.793	.795	.793	.793	.793	.793	.795	.790	.790	.788	.788	.783	.785	.790	.785	.770
.783	.788	.790	.790	.790	.793	.790	.793	.790	.790	.788	.788	.775	.783	.783	.780	.790	.783	.773
.778	.780	.780	.783	.785	.785	.785	.785	.783	.785	.783	.780	.778	.778	.775	.773	.785	.773	.765
.775	.780	.780	.780	.780	.780	.780	.780	.780	.778	.778	.780	.770	.773	.770	.770	.780	.773	.768
.780	.780	.783	.785	.785	.785	.785	.785	.783	.785	.785	.783	.780	.778	.778	.775	.785	.778	.768
.788	.790	.793	.795	.795	.795	.795	.795	.808	.795	.795	.790	.790	.788	.785	.785	.795	.790	.775
.798	.800	.808	.808	.808	.813	.810	.808	.805	.810	.805	.803	.795	.793	.800	.790	.805	.795	.783

TABLE IV

ULTRASONIC THICKNESS TRAVERSE FOR HEAT-A PLATE

.782	.780	.765	.776	.775	.780	.782	.782	.780
.780	.782	.780	.783	.782	.786	.784	.782	.782
.785	.788	.785	.784	.784	.786	.786	.784	.784
.788	.785	.785	.782	.784	.786	.788	.786	.790
.786	.789	.785	.786	.786	.790	.790	.788	.788
.788	.794	.789	.788	.784	.782	.786	.790	.788
.790	.790	.786	.786	.780	.786	.790	.790	.792
.790	.792	.788	.786	.788	.788	.788	.790	.790
.792	.790	.790	.786	.788	.790	.788	.788	.788
.790	.790	.788	.788	.786	.788	.790	.786	.786
.788	.790	.790	.790	.788	.788	.786	.786	.786
.790	.790	.786	.786	.786	.786	.786	.784	.784
.788	.785	.784	.786	.784	.782	.784	.782	.784

6"

6"

84"

60"

.780	.785	.788	.783	.775	.790	.770	.785	.790	.790	.795	.793	.792	.788	.788	.792	.790	.790	.790
.780	.787	.790	.780	.775	.793	.795	.785	.783	.795	.794	.795	.793	.790	.788	.790	.770	.788	.783
.783	.783	.790	.788	.785	.793	.793	.793	.794	.796	.797	.795	.795	.793	.790	.790	.772	.787	.783
.783	.787	.786	.793	.793	.794	.792	.793	.793	.794	.794	.798	.794	.790	.790	.788	.780	.793	.790
.782	.777	.783	.790	.795	.793	.792	.792	.794	.795	.796	.797	.794	.792	.793	.777	.776	.789	.785
.780	.785	.782	.788	.787	.790	.787	.791	.793	.794	.795	.795	.793	.790	.790	.788	.790	.775	.793
.780	.780	.782	.775	.777	.784	.790	.788	.793	.795	.793	.785	.790	.790	.790	.789	.790	.793	.790
.780	.784	.787	.780	.773	.780	.785	.775	.793	.794	.794	.793	.790	.790	.794	.791	.793	.773	.790
.770	.785	.788	.790	.778	.780	.790	.787	.795	.795	.794	.794	.792	.793	.792	.790	.790	.772	.786
.773	.787	.790	.793	.775	.777	.782	.780	.797	.798	.795	.794	.794	.795	.793	.790	.793	.790	.790
.745	.787	.790	.793	.786	.785	.783	.797	.798	.798	.795	.794	.794	.794	.792	.790	.790	.790	.791
.770	.790	.790	.794	.786	.782	.785	.800	.798	.805	.795	.795	.795	.795	.793	.790	.777	.790	.790
.757	.787	.786	.794	.787	.777	.800	.795	.795	.798	.796	.795	.794	.794	.793	.787	.780	.790	.792
.764	.788	.790	.794	.795	.781	.795	.800	.795	.798	.795	.794	.793	.792	.791	.782	.792	.790	.791
.782	.787	.791	.793	.796	.786	.797	.795	.798	.798	.795	.795	.794	.795	.794	.790	.790	.794	.791
.780	.790	.792	.795	.780	.797	.797	.795	.795	.797	.797	.797	.797	.794	.793	.795	.795	.795	.790
.773	.787	.790	.793	.775	.793	.796	.795	.796	.796	.794	.795	.794	.793	.793	.795	.794	.792	.793
.770	.787	.790	.793	.793	.797	.795	.797	.797	.796	.795	.795	.795	.795	.794	.793	.792	.793	.792
.774	.786	.790	.794	.795	.796	.795	.797	.795	.796	.800	.800	.797	.795	.794	.793	.793	.792	.793
.760	.787	.793	.795	.796	.796	.800	.797	.795	.795	.795	.795	.795	.794	.794	.778	.793	.792	.790
.785	.787	.793	.795	.796	.798	.797	.798	.798	.798	.797	.796	.796	.796	.795	.784	.793	.793	.792
.783	.785	.790	.799	.799	.797	.798	.800	.797	.800	.795	.796	.787	.785	.792	.780	.793	.793	.791
.785	.790	.793	.795	.795	.797	.797	.798	.798	.793	.795	.793	.787	.785	.791	.791	.782	.783	.783
.788	.793	.796	.795	.795	.797	.796	.797	.797	.791	.797	.792	.786	.791	.793	.793	.786	.779	.790
.784	.788	.791	.795	.796	.797	.797	.798	.799	.791	.801	.788	.798	.796	.795	.795	.793	.794	.793
.785	.790	.791	.795	.796	.797	.798	.798	.799	.796	.798	.797	.797	.796	.796	.796	.796	.801	.792
.788	.790	.791	.794	.795	.797	.797	.798	.796	.791	.798	.791	.795	.798	.794	.795	.795	.795	.793
.786	.789	.793	.795	.796	.798	.797	.799	.799	.800	.801	.792	.796	.796	.800	.796	.790	.795	.793
.786	.790	.794	.796	.800	.799	.800	.800	.799	.801	.799	.801	.798	.801	.797	.799	.791	.796	.794
.784	.787	.792	.798	.798	.799	.800	.799	.801	.801	.799	.801	.802	.799	.797	.797	.798	.795	.793
.785	.790	.793	.794	.797	.803	.797	.798	.799	.799	.799	.797	.797	.800	.797	.797	.798	.796	.794
.791	.791	.793	.784	.797	.797	.798	.798	.801	.794	.800	.797	.798	.800	.800	.800	.793	.789	.800
.791	.791	.795	.790	.797	.797	.797	.797	.800	.793	.795	.800	.800	.800	.800	.800	.775	.783	.795
.791	.791	.792	.797	.797	.797	.796	.796	.796	.797	.802	.801	.801	.799	.800	.799	.789	.796	.794
.790	.792	.795	.795	.795	.796	.797	.796	.798	.797	.802	.800	.798	.800	.802	.800	.779	.800	.794
.788	.772	.790	.796	.797	.800	.800	.800	.798	.892	.800	.800	.799	.799	.799	.797	.791	.795	.793
.787	.778	.797	.797	.799	.799	.797	.798	.801	.800	.797	.796	.797	.797	.799	.787	.773	.795	.793
.788	.791	.787	.796	.796	.799	.798	.779	.801	.800	.801	.801	.798	.800	.800	.797	.786	.796	.794
.789	.792	.795	.796	.797	.799	.798	.788	.801	.802	.791	.799	.798	.799	.799	.779	.787	.799	.799
.788	.791	.794	.796	.796	.801	.798	.799	.801	.801	.790	.798	.799	.799	.797	.783	.788	.795	.794
.786	.791	.794	.796	.796	.798	.798	.797	.801	.801	.797	.795	.798	.797	.796	.783	.784	.794	.794
.785	.790	.792	.795	.797	.798	.798	.785	.801	.800	.798	.783	.800	.795	.800	.787	.787	.796	.794
.786	.790	.793	.796	.796	.798	.790	.788	.800	.799	.800	.790	.795	.795	.798	.786	.786	.795	.795
.785	.790	.792	.794	.795	.797	.800	.786	.799	.796	.796	.786	.796	.797	.796	.786	.786	.794	.793
.786	.788	.795	.795	.796	.796	.792	.782	.796	.796	.800	.790	.796	.796	.796	.790	.779	.792	.790
.785	.787	.793	.794	.795	.797	.795	.783	.797	.797	.795	.783	.796	.795	.795	.777	.779	.792	.791
.784	.790	.790	.795	.794	.793	.794	.795	.795	.780	.798	.780	.795	.795	.738	.794	.783	.792	.790
.780	.788	.790	.793	.795	.793	.794	.793	.795	.787	.795	.780	.794	.794	.794	.775	.777	.793	.790
.785	.790	.785	.793	.794	.777	.795	.796	.797	.795	.795	.785	.795	.794	.794	.790	.788	.789	.788
.787	.794	.788	.793	.792	.778	.794	.795	.793	.792	.780	.793	.795	.789	.788	.777	.774	.788	.787
.784	.785	.793	.792	.795	.777	.796	.795	.787	.795	.786	.796	.793	.794	.794	.793	.786	.794	.790
.782	.786	.791	.793	.794	.785	.794	.794	.787	.794	.794	.794	.794	.792	.765	.752	.775	.790	.790
.784	.788	.790	.793	.794	.794	.795	.795	.798	.797	.796	.782	.794	.793	.792	.780	.773	.794	.794
.787	.789	.795	.795	.797	.795	.795	.794	.798	.800	.796	.775	.795	.793	.792	.775	.747	.793	.790
.787	.787	.788	.793	.795	.794	.792	.793	.795	.797	.794	.794	.790	.783	.791	.784	.782	.793	.789
.787	.788	.789	.775	.793	.793	.793	.793	.792	.790	.793	.794	.787	.793	.786	.787	.783	.787	.787
.787	.790	.775	.780	.793	.793	.798	.794	.795	.783	.793	.794	.783	.791	.784	.796	.790	.794	.789

TABLE V — HEAT B PLATE, PLATE NO. 1
ULTRASONIC THICKNESS TRAVERSE DATA

Table VI — Heat B Plate, Plate No. 2. Ultrasonic thickness traverse data. Plate dimensions 120" × 300", with 6" grid spacing.

.783	.784	.785	.786	.790	.791	.795	.797	.797	.796	.800	.800	.793	.794	.792	.793	.793	.793	.789
.785	.786	.786	.790	.790	.793	.795	.797	.799	.797	.797	.800	.796	.796	.793	.794	.793	.792	.793
.784	.788	.788	.791	.792	.795	.796	.797	.795	.796	.797	.800	.800	.797	.797	.797	.797	.796	.787
.786	.786	.789	.790	.791	.795	.790	.795	.797	.799	.800	.800	.795	.797	.796	.797	.796	.796	.793
.785	.784	.788	.790	.791	.792	.791	.796	.799	.799	.797	.800	.800	.797	.795	.795	.795	.794	.787
.786	.785	.787	.790	.791	.795	.796	.798	.800	.800	.797	.800	.800	.797	.795	.798	.797	.793	.787
.786	.786	.789	.790	.791	.793	.797	.798	.800	.800	.798	.798	.797	.797	.796	.795	.794	.788	.800
.785	.787	.787	.790	.791	.784	.800	.800	.800	.800	.798	.798	.797	.798	.797	.797	.797	.793	.795
.778	.785	.788	.790	.793	.793	.800	.800	.797	.801	.798	.798	.798	.797	.797	.797	.790	.792	.790
.783	.786	.787	.789	.792	.794	.797	.799	.801	.801	.800	.797	.798	.797	.796	.794	.795	.794	.792
.787	.790	.791	.791	.792	.795	.799	.797	.798	.803	.797	.798	.798	.799	.797	.795	.793	.794	.792
.787	.789	.790	.791	.793	.795	.800	.800	.796	.800	.798	.800	.800	.797	.796	.795	.795	.795	.794
.787	.790	.790	.791	.793	.795	.798	.799	.799	.799	.797	.798	.797	.798	.796	.796	.795	.792	.797
.789	.789	.790	.794	.794	.797	.799	.800	.786	.801	.797	.798	.800	.798	.799	.797	.796	.794	.787
.789	.790	.793	.795	.796	.800	.800	.801	.795	.802	.792	.797	.794	.796	.796	.794	.795	.794	.792
.783	.791	.792	.794	.795	.799	.800	.800	.801	.801	.790	.797	.799	.799	.797	.795	.793	.795	.794
.787	.790	.792	.792	.793	.797	.799	.797	.800	.801	.797	.796	.798	.797	.797	.795	.793	.794	.794
.786	.791	.790	.791	.794	.797	.798	.800	.800	.803	.800	.800	.800	.798	.799	.797	.797	.795	.794
.786	.794	.792	.794	.795	.800	.800	.801	.801	.801	.802	.800	.800	.800	.795	.793	.797	.794	.787
.784	.785	.791	.793	.795	.797	.800	.800	.801	.801	.797	.797	.798	.798	.799	.797	.796	.796	.783
.787	.791	.791	.792	.795	.800	.798	.798	.801	.800	.800	.798	.799	.799	.798	.798	.795	.795	.790
.784	.790	.793	.795	.795	.788	.800	.800	.801	.799	.789	.802	.799	.799	.798	.798	.798	.795	.790
.786	.790	.793	.794	.795	.796	.800	.800	.801	.800	.800	.800	.799	.799	.798	.797	.796	.796	.792
.784	.788	.790	.792	.796	.797	.799	.800	.798	.800	.805	.803	.800	.800	.791	.798	.798	.797	.792
.787	.787	.793	.792	.793	.795	.795	.797	.794	.800	.800	.802	.802	.802	.800	.800	.800	.800	.793
.788	.790	.790	.792	.793	.794	.795	.797	.798	.799	.803	.803	.805	.802	.802	.801	.800	.800	.794
.790	.790	.790	.791	.793	.797	.800	.798	.801	.800	.802	.805	.803	.803	.803	.801	.800	.800	.795
.785	.783	.790	.790	.793	.795	.799	.797	.798	.801	.799	.801	.799	.795	.800	.801	.800	.800	.798
.785	.783	.790	.791	.793	.795	.799	.798	.797	.800	.801	.805	.803	.801	.802	.800	.801	.800	.797
.785	.791	.790	.791	.795	.795	.796	.796	.800	.790	.796	.796	.802	.804	.802	.802	.801	.798	.798
.784	.785	.790	.790	.793	.795	.795	.796	.799	.799	.799	.800	.798	.799	.799	.800	.797	.797	.796
.782	.779	.788	.790	.790	.794	.798	.795	.796	.800	.798	.797	.798	.798	.799	.796	.797	.797	.794
.781	.782	.790	.790	.791	.794	.794	.795	.795	.796	.798	.800	.798	.798	.797	.796	.796	.797	.796
.785	.780	.784	.790	.795	.795	.796	.796	.796	.796	.800	.798	.802	.799	.798	.796	.795	.796	.794
.785	.786	.787	.790	.793	.792	.795	.796	.796	.797	.798	.799	.800	.798	.797	.795	.795	.796	.794
.784	.784	.789	.790	.791	.791	.793	.793	.796	.791	.799	.798	.798	.798	.798	.797	.796	.797	.795
.785	.780	.788	.790	.790	.791	.796	.796	.800	.800	.798	.797	.798	.798	.798	.797	.797	.797	.794
.784	.779	.783	.788	.791	.793	.794	.795	.795	.797	.800	.797	.797	.800	.798	.797	.797	.796	.794
.785	.785	.785	.785	.785	.791	.795	.794	.796	.796	.798	.797	.798	.798	.798	.797	.797	.797	.780
.785	.786	.784	.783	.791	.793	.794	.793	.795	.795	.800	.800	.796	.797	.795	.796	.797	.794	.770
.785	.785	.788	.790	.790	.793	.795	.796	.797	.797	.795	.795	.797	.797	.797	.797	.796	.796	.793
.786	.786	.788	.790	.791	.793	.795	.795	.797	.797	.798	.798	.798	.800	.798	.794	.795	.795	.793
.785	.786	.788	.790	.791	.790	.794	.795	.797	.794	.798	.798	.798	.797	.797	.797	.796	.796	.795
.781	.781	.785	.786	.788	.790	.791	.793	.793	.795	.798	.797	.797	.797	.796	.795	.795	.790	.791
.780	.782	.789	.788	.790	.790	.789	.793	.795	.795	.795	.797	.795	.797	.796	.794	.795	.796	.787
.781	.780	.789	.790	.789	.791	.795	.794	.795	.795	.900	.800	.800	.800	.796	.790	.795	.796	.787
.782	.785	.789	.789	.795	.793	.794	.796	.793	.798	.794	.798	.795	.793	.792	.794	.795	.793	.787
.784	.786	.790	.790	.793	.792	.797	.798	.797	.798	.798	.797	.797	.797	.796	.797	.797	.792	.786
.784	.786	.788	.788	.788	.789	.789	.795	.792	.796	.794	.795	.797	.794	.795	.794	.794	.790	.786

TABLE VI - HEAT B PLATE, PLATE NO. 2
ULTRASONIC THICKNESS TRAVERSE DATA

2.7.1   <u>Dimensional, Soundness and Hardness Inspection</u> (Cont'd.)

Plate surfaces were characterized by a rather tenacious, crazed mill scale which was not readily removed by grit blasting. The thickness of the scale was approximately 0.001 inches. Occasional laps and surface imbedded inclusions were found in Heat B plate. These surface defects apparently resulted during plate rolling. Occasionally, such defects behaved as initiation sites for cracks for cracks induced during fatigue cracking of the PTC specimens. Figures 11 through 14 illustrate the visual defects found in the Heat B plates.

The hardness of the as-received Heat A plate averaged 34 Rockwell C, and ranged from 32 to 34.5 Rockwell C. These values are at the limit specified in DMS 1835. The hardness of the as-received Heat B plate averaged 30.3 Rockwell "C" and ranged from 28.5 to 32.1. These values are well within the requirements.

2.7.2   <u>Metallographic Examination</u>

Metallographic specimens were examined from plate in the as-received mill-annealed condition. Both transverse and longitudinal sections were examined. Figures 15 and 16 illustrate characteristic micro-structures for the 18Ni-7Co-5Mo alloy. Banding is more pronounced on transverse than on longitudinal sections. The Figures illustrate types of inclusion typically observed in the 18-7-5 alloy. The type illustrated in Figure 15 is often gold colored and predominately occurs within light etching bands. The extremities of the inclusions appear to be bounded by sharp cornered voids. The voids may have been

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DIAGRAM SHOWING VISUAL DEFECTS, PITS AND SCARS
HEAT-B, PLATE 1 – SIDE 1

FIGURE 11

DIAGRAM SHOWING VISUAL DEFECTS, PITS AND SCARS
HEAT-B, PLATE 1 – SIDE 2

FIGURE 12

DIAGRAM SHOWING VISUAL DEFECTS, PITS AND SCARS
HEAT-B, PLATE 2 – SIDE 1
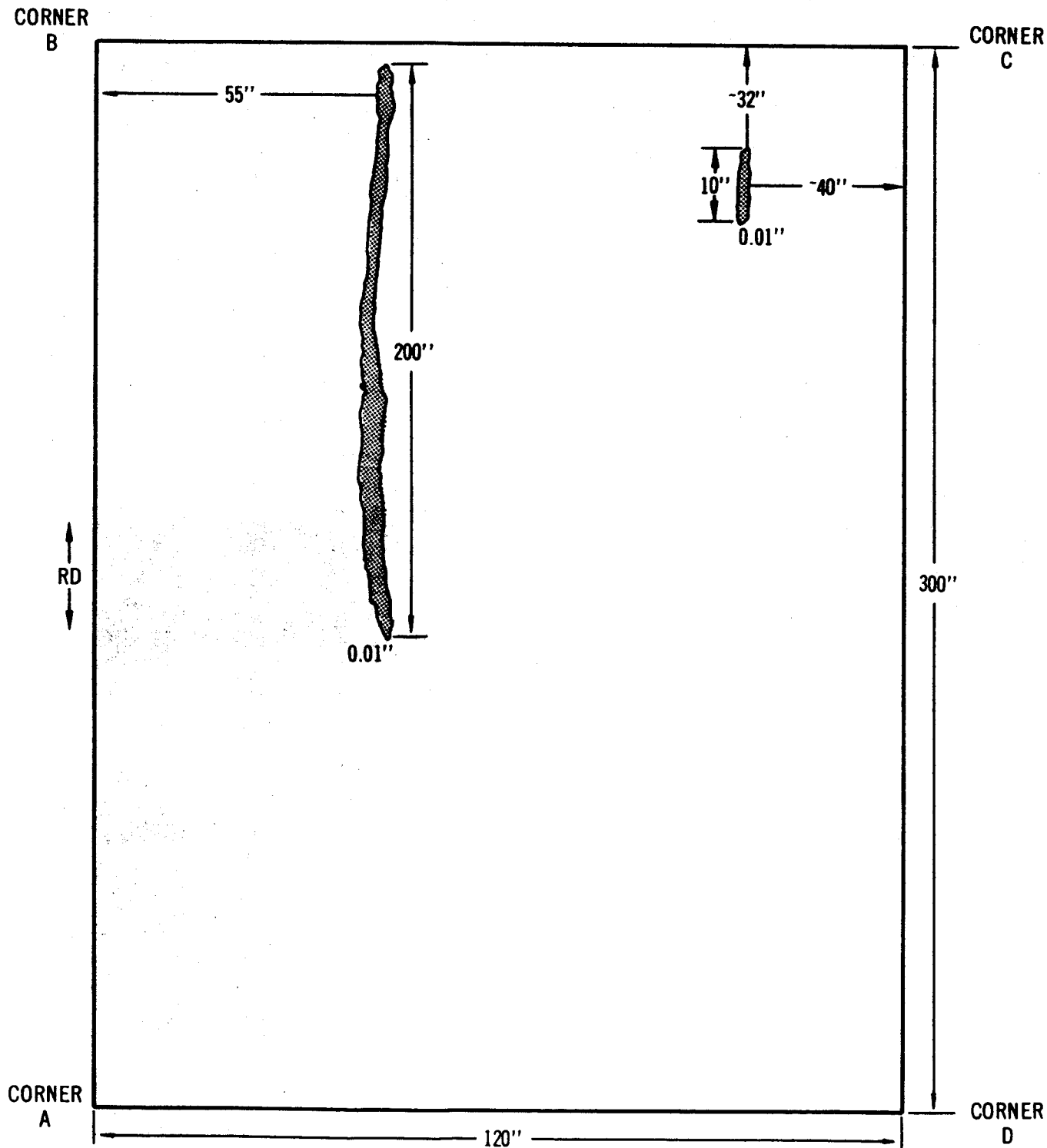
FIGURE 13

DIAGRAM SHOWING VISUAL DEFECTS, PITS AND SCARS
HEAT-B, PLATE 2 – SIDE 2
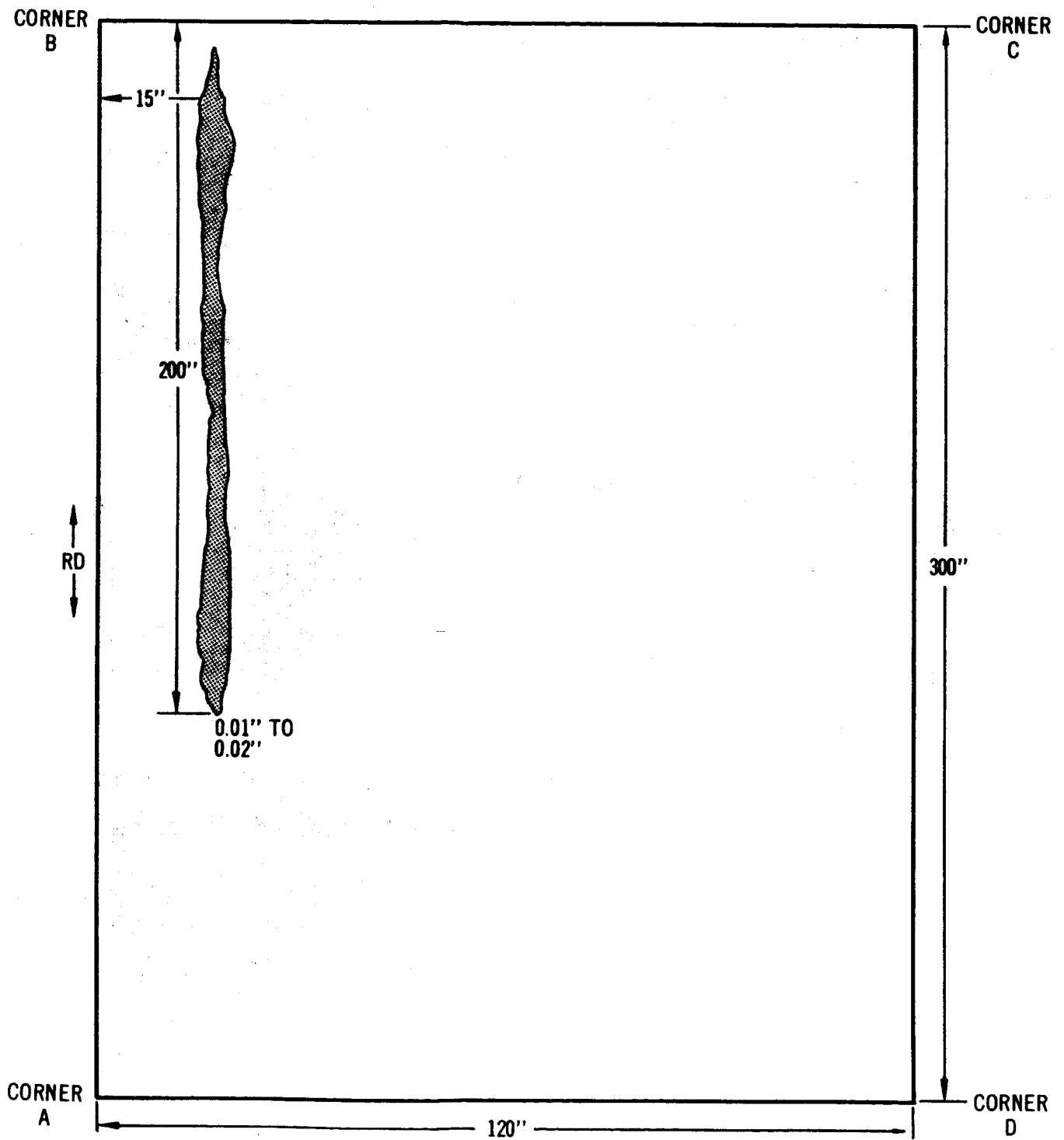
FIGURE 14
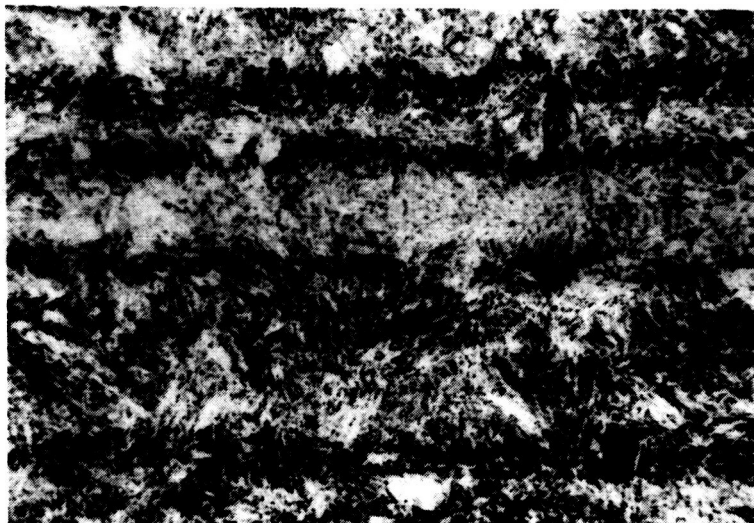
TYPICAL TRANSVERSE SECTION ILLUSTRATING
CHARACTERISTIC BANDED APPEARANCE
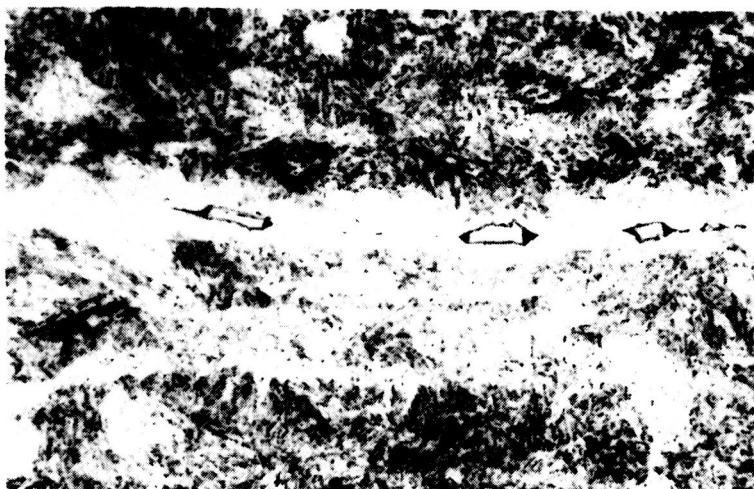
SECTION SHOWING INCLUSIONS

AS RECEIVED HEAT-A PLATE

250X

ETCH: 50 ML HCL
25 ML HNO_3
I GR $CuCl_2$
150 ML H_2O

FIGURE 15

TYPICAL TRANSVERSE SECTION - HEAVY ETCH
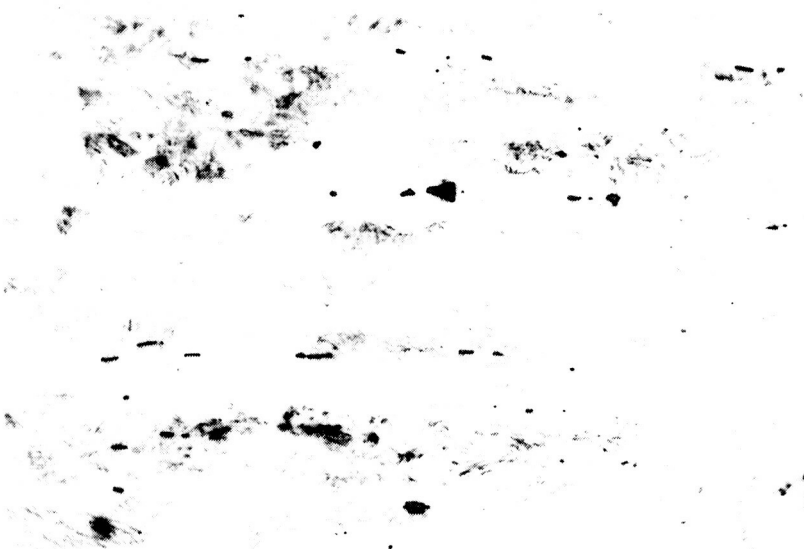
SECTION SHOWING INCLUSIONS - LIGHT ETCH

AS RECEIVED HEAT-B PLATE

FIGURE 16

250X

ETCH: 50 ML HCl
25 ML HNO_3
1 GR $CuCl_2$
150 ML H_2O

31

2.7.2   Metallographic Examination (Cont'd.)

produced by selective etching; however, in all probability they
were induced during plate rolling when the inclusions failed to
deform and elongate in the same way as the surrounding material.
This type of inclusion is tentatively identified in a later section
as titanium nitride. As will be seen, titanium nitride inclusions
represent a major detriment to toughness in this alloy, especially
in welds. Typical smaller inclusions are illustrated in Figure 16.

Inclusion content determinations were made on Heats I, A and B plate
in accordance with ASTM Designation E-45, Method A. Table VII
presents the average values determined by the suppliers, Newport
News, and Douglas. The values are within the limits specified with
the exceptions of the thin series for Type B and D. The majority
of the inclusions were the angular type presumed to be primarily
titanium nitrides. Some differences in the inclusion counts are
indicated. However, the limited data prohibit the formulation of
decisive conclusions concerning the apparent differences.

2.7.3   Tensile Property Check

Twelve 0.505 tensile specimens aged at $900^{\circ}F$ for 3 hours, were
tensile tested to determine whether or not Heats A and B plate
possessed the minimum property requirements specified in DMS 1835.
The results are presented in Table VIII. The properties exceed the
minimum requirements of the specifications.

TABLE VII

INCLUSION CONTENT DETERMINED IN ACCORDANCE WITH ASTM DESIGNATION E-45 METHOD A

HEAT I

SOURCE	TYPE A		TYPE B		TYPE C		TYPE D	
	Thin	Heavy	Thin	Heavy	Thin	Heavy	Thin	Heavy
Douglas	1.0 2.0	0 0	1.0 0	0 0	0 0	0 0	1 2	0 0
Avg.	1.5	0	0.5	0	0	0	1.5	0

HEAT A

SOURCE	TYPE A		TYPE B		TYPE C		TYPE D	
	Thin	Heavy	Thin	Heavy	Thin	Heavy	Thin	Heavy
Newport	0	0	0.14	0	0	0	1.88	0
Douglas	1.0	0.75	1.2	1.0	0	0	1.0	0
U.S.S.	1.0	0	1.5	0	0	0	1.5	0
Avg.	0.7	0.25	0.9	0.3	0	0	1.6	0

HEAT B

SOURCE	TYPE A		TYPE B		TYPE C		TYPE D	
	Thin	Heavy	Thin	Heavy	Thin	Heavy	Thin	Heavy
Newport	0	0	1.75	0	0	0	2.75	1.0
Douglas	0	0	1.50	0	1.50	0.5	0.5	0.5
Avg.	0	0	1.6	0	0.75	0.25	1.6	0.75

TABLE VIII

TENSILE DATA ON HEATS A AND B PLATE
TO CHECK SPECIFICATION CONFORMANCE

SPEC. No.	SPECIMEN ORIENTATION	0.2% YIELD STRESS, (KSI)	ULTIMATE STRESS, (KSI)	% ELONG. (2 in. GAGE)	% RED. IN AREA
HEAT-A PLATE TENSILE DATA					
AP 31	L	253.0	259.0	11.0	45.5
AP 32	L	252.0	258.5	11.0	44.9
AP 33	L	253.6	258.8	11.0	44.0
AP 34	T	255.0	260.8	8.0	32.5
AP 35	T	252.0	260.0	10.0	36.6
AP 36	T	254.0	260.3	9.0	38.8
HEAT-B PLATE TENSILE DATA					
P-31	L	254.5	264.0	9.0	41.9
P-32	L	257.0	265.0	11.0	41.3
P-33	L	253.5	263.0	8.0	38.5
P-34	T	265.5	270.0	8.0	33.4
P-35	T	264.0	267.5	8.0	33.4
P-36	T	259.0	269.0	7.0	34.4

NOTES:

1. L = Longitudinal

    T = Transverse

2. All results obtained with 0.505-in. diameter specimens

3. Aged at 900°F for 3 hours

2.7.4   <u>Effect of Rolling Direction and Aging Treatment on Tensile Properties</u>

Figures 17 through 22 show the effect of aging time and temperature on the uniaxial tensile properties of both transverse and longitudinal 0.505-in. diameter specimens from the Heats A and B plate. Data shown are for aging temperatures of 875, 900 and 950°F and aging times of 1, 3, 6, and 12 hours. Each point represents an individual test specimen. Data for Heat 1 are shown in Figure 23. Specimens were aged for times of 1, 3, 8, or 15 hours. Yield stress data are not illustrated in Figure 23 since values for the range were not obtained.

Figures 24 and 25 illustrate the comparative strength and ductility of the three plate heats. Ultimate strength alone is plotted in Figure 24 since the alloy is characterized by yield-to-ultimate strength ratios generally exceeding 0.9. Tabulated data on Heats 1, A, and B are presented in Appendix IV.

The data may be summarized as follows:

1. Aging at 875°F is characterized by a monotonic increase in tensile strength with increasing aging time (Figure 24) for the three plate heats. The absolute strengths that are achieved and the rates of strengthening differ. A maximum difference of approximately 20 KSI exists between Heat 1, the lowest strength, and Heat B. Heats 1 and A differ by about 5 KSI over the entire aging time range examined. Heat B appears to strengthen at a more rapid rate than either Heats 1 or A. Unexpectedly high strength, approaching 300-KSI, was attained by Heat-B plate

Effect of Rolling Direction and Aging Treatment on Tensile Properties
(Cont'd.)

after a 12 hour aging exposure.

2. Heats I and A, after 900°F aging, exhibit about the same strengthening response (Figure 24). The strength levels are approximately equivalent and appear to reach a relative plateau after 6 hours. Heat B exhibits substantially higher strength over the entire range of aging times. Heat B overages at 900°F as indicated by the drop in strength after 6 hours. Overaging does not occur for Heats I or A at the 900°F aging temperature.

3. At 950°F all heats reach a peak strength after 3 hours, (Figure 24). After 3 hours, overaging occurs as depicted by a steady drop in strength with increasing aging time. Again Heat B exhibits the highest tensile strength. Heat I, which was lower in strength than Heat A after 875°F aging and about equal after 900°F, exhibits intermediate strength after 950°F aging.

4. Two other temperatures were investigated for Heat I. These were 925°F and 1000°F. The 925°F aging cycle very nearly produces the same strengths as the 900°F cycle. The 1000°F cycle exhibits immediate overaging (Figure 23).

5. Ductility (as measured by per cent elongation and reduction in area) for Heats I and A are similar for all aging times and temperatures and are slightly higher than the values for Heat B. Ductility in the transverse direction is generally inferior to that in the longitudinal direction.

2.7.4 Effect of Rolling Direction and Aging Treatment on Tensile Properties (Cont'd.)

Figure 25 shows a scatterband plot showing the effect of aging times and temperatures on ductility for Heats A and B. If Heat I were shown, it would be within the values drawn for Heat A.

6. Although transverse strengths are generally greater than longitudinal, some notable exceptions were observed: Heat B, $900^\circ F$ for 12 hours, (Figure 21) and $950^\circ F$ for all aging times (Figure 22). Thus orientation effects are not definitive.

7. The above observations demonstrate that rather striking differences can exist in the aging response of nominally 18Ni-7Co-5Mo plate.

2.7.5 Effects of Aging Treatment on Hardness

The dependence of hardness on the aging treatment is depicted graphically in Figure 26 for plate from the three heats. Each point represents the average of four to eight indentations. As may be seen, hardness remains very nearly constant over a wide range of aging times and temperatures. Heats I and B are slightly harder than Heat A. This agrees with the relative strength of Heat B plate, which had the highest tensile properties. However, Heat I generally exhibited the lowest strength. Hardness does not appear to correlate very well with tensile strength.

EFFECT OF AGING TIME AT 875°F ON THE UNIAXIAL TENSILE PROPERTIES OF HEAT—A 18Ni–7Co–5Mo AIRMELTED PLATE

◇ — ULTIMATE TENSILE STRENGTH
○ — 0.2% OFFSET YIELD
△ — % ELONGATION (IN 2")
□ — % REDUCTION IN AREA

OPEN SYMBOLS – LONGITUDINAL
SOLID SYMBOLS – TRANSVERSE

FIGURE 17

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EFFECT OF AGING TIME AT 900°F ON THE UNIAXIAL TENSILE
PROPERTIES OF HEAT – A 18Ni–7Co–5Mo AIRMELTED PLATE

ULTIMATE TENSILE STRENGTH
0.2% OFFSET YIELD
% ELONGATION (IN 2")
% REDUCTION IN AREA

OPEN SYMBOLS – LONGITUDINAL
SOLID SYMBOLS – TRANSVERSE

FIGURE 18

EFFECT OF AGING TIME AT 950°F ON THE UNIAXIAL TENSILE PROPERTIES OF HEAT – A 18Ni-7Co-5Mo AIRMELTED PLATE

ULTIMATE TENSILE STRENGTH
0.2% OFFSET YIELD
% ELONGATION (IN 2")
% REDUCTION IN AREA

OPEN SYMBOLS – LONGITUDINAL
SOLID SYMBOLS – TRANSVERSE
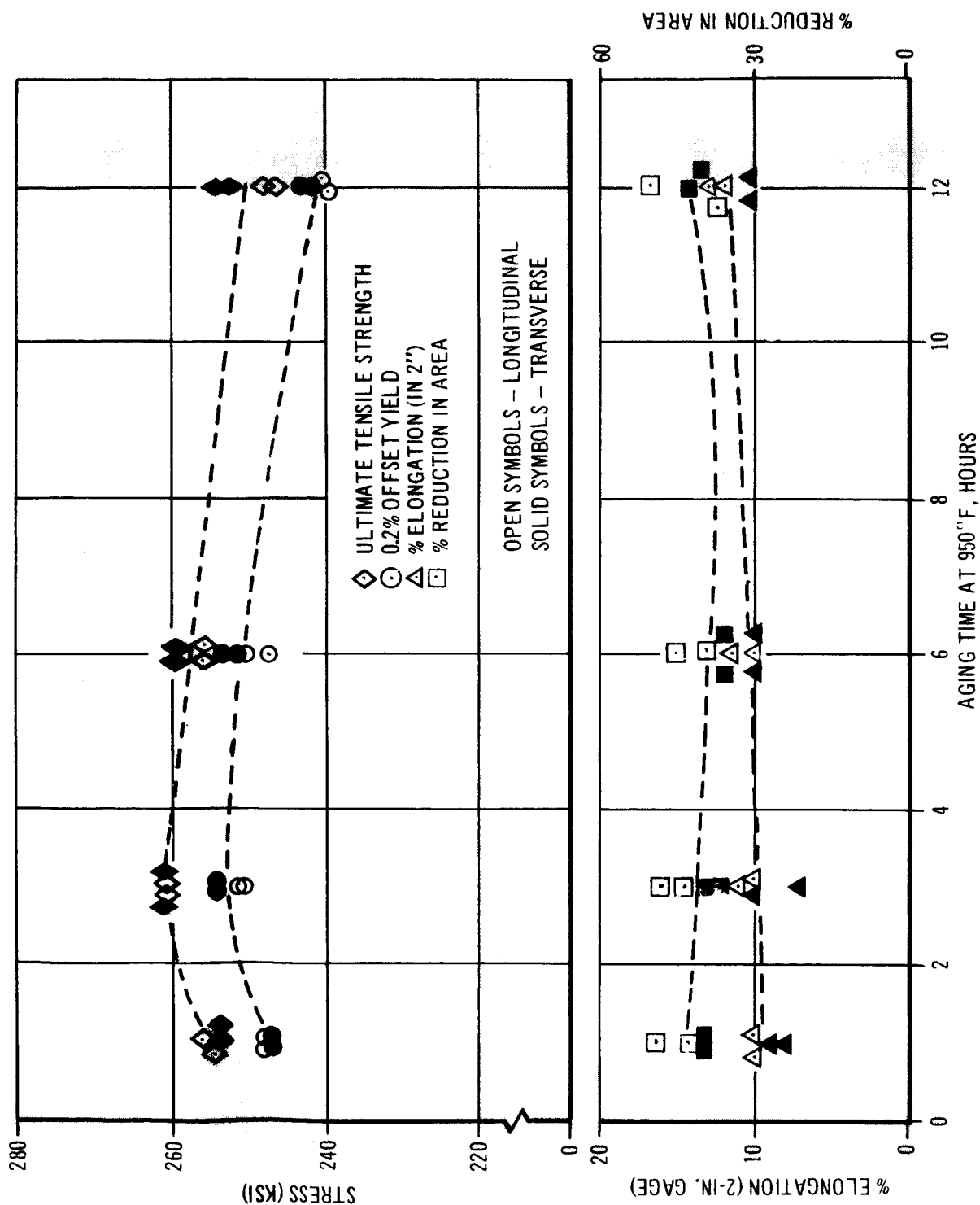
FIGURE 19

EFFECT OF AGING TIME AT 875°F ON THE UNIAXIAL TENSILE PROPERTIES OF HEAT B 18Ni-7Co-5Mo AIRMELTED PLATE

◊ ULTIMATE TENSILE STRENGTH
○ 0.2% OFFSET YIELD
△ % ELONGATION (IN 2")
□ % REDUCTION IN AREA

OPEN SYMBOLS LONGITUDINAL
SOLID SYMBOLS TRANSVERSE

FIGURE 20

41

EFFECT OF AGING TIME AT 900°F* ON THE UNIAXIAL TENSILE
PROPERTIES OF HEAT B 18Ni–7Co–5Mo AIRMELTED PLATE
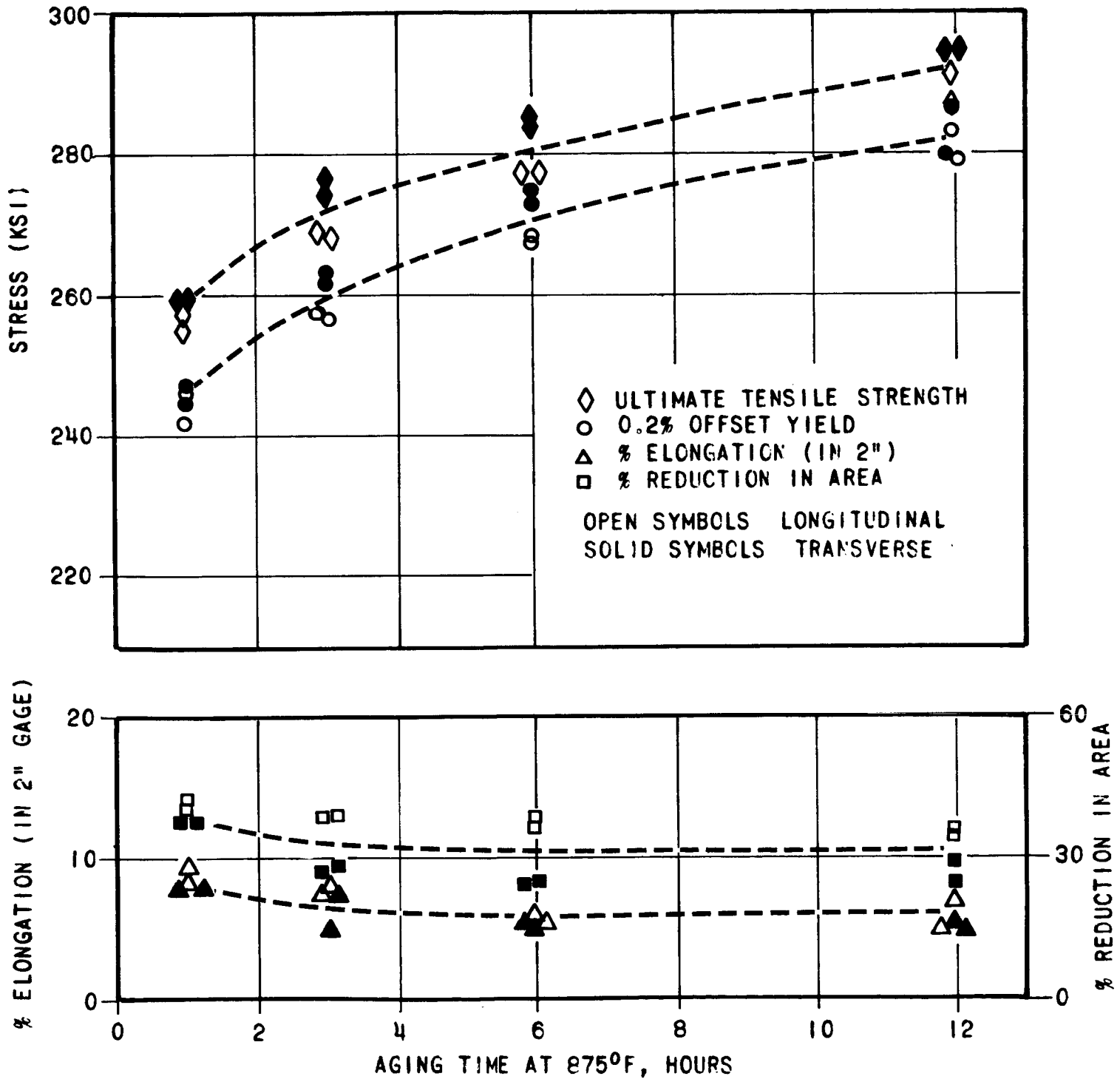
◇ ULTIMATE TENSILE STRENGTH
○ 0.2% OFFSET YIELD
△ % ELONGATION (IN 2")
□ % REDUCTION IN AREA
OPEN SYMBOLS — LONGITUDINAL
SOLID SYMBOLS — TRANSVERSE

* 3 HOUR SPECIMENS INADVERTENTLY AGED AT 915°F.

FIGURE 21

EFFECT OF AGING TIME AT 950° F ON THE UNIAXIAL TENSILE
PROPERTIES OF HEAT B 18Ni 7Co-5Mo AIRMELTED PLATE

◇   ULTIMATE TENSILE STRENGTH
○   0.2% OFFSET YIELD
△   % ELONGATION (IN 2")
□   % REDUCTION IN AREA
OPEN SYMBOLS − LONGITUDINAL
SOLID SYMBOLS − TRANSVERSE
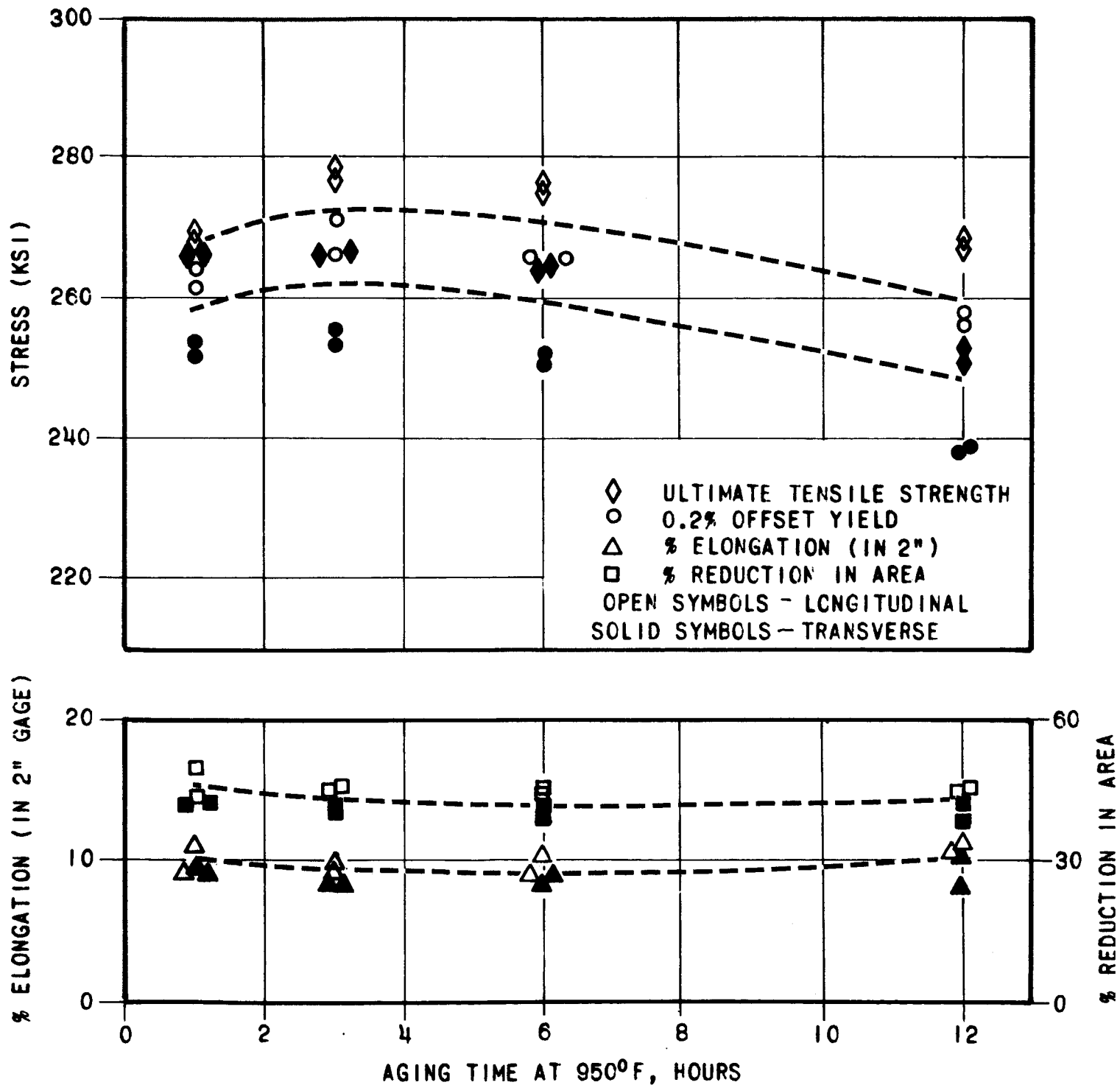
FIGURE 22

EFFECT OF AGING TIME AT TEMPERATURES FROM 875 TO 1000°F ON THE UNIAXIAL TENSILE PROPERTIES OF HEAT-1 18Ni-7Co-5Mo AIRMELTED PLATE

FIGURE 23

44
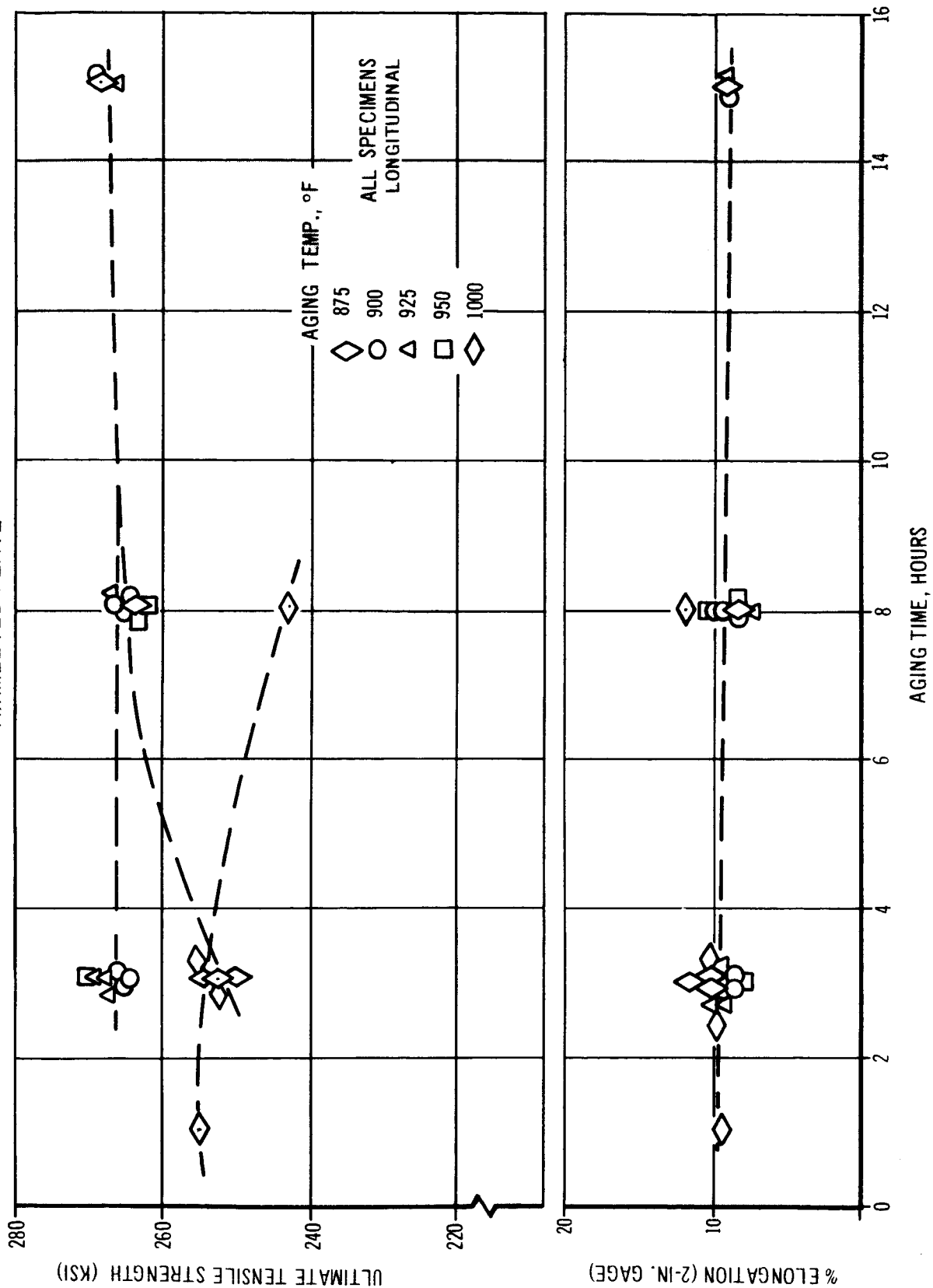
EFFECT OF AGING TIME AND TEMPERATURES ON ULTIMATE TENSILE STRENGTH OF HEATS 1, A, AND B PLATE
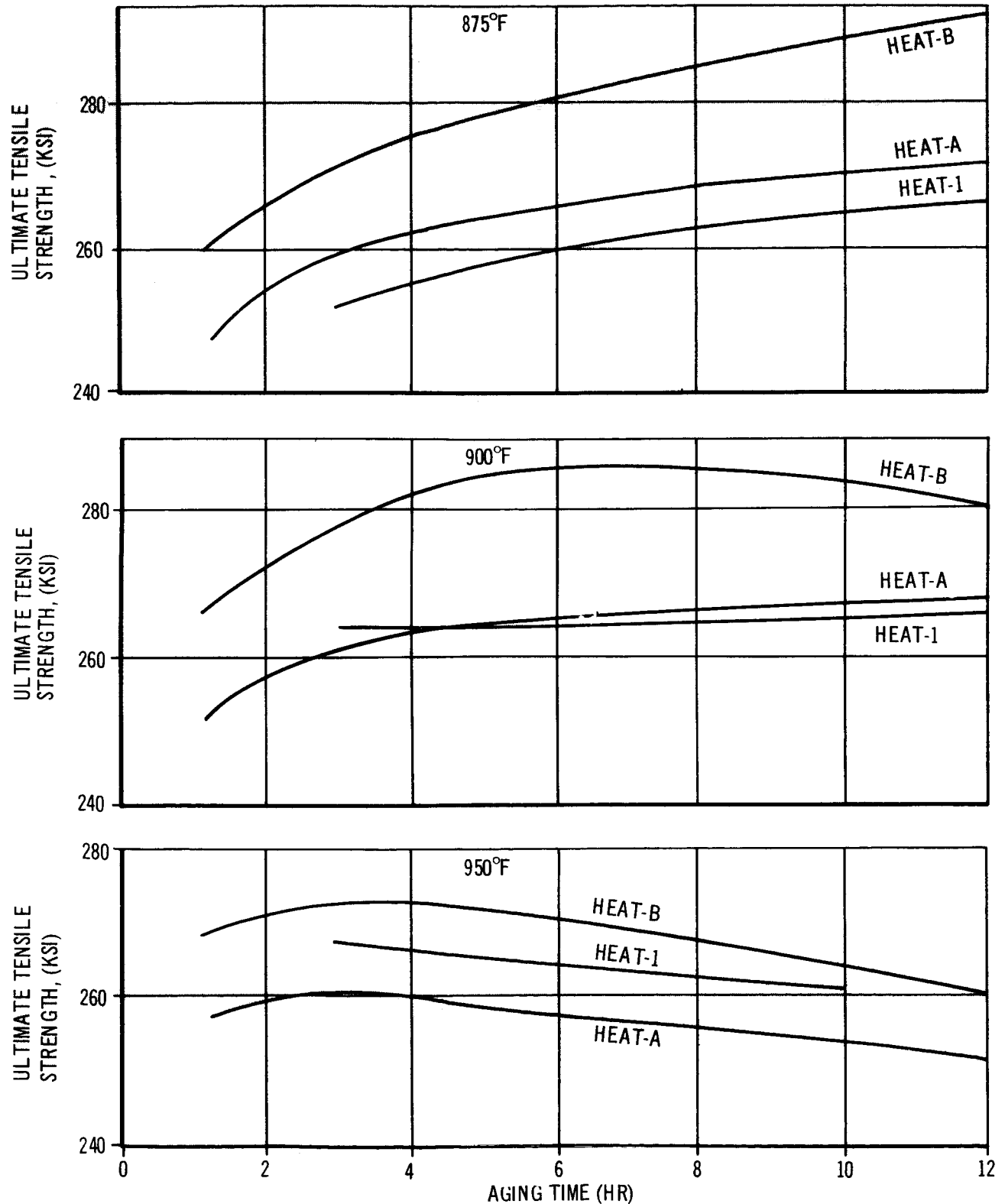
FIGURE 24

EFFECT OF AGING TIME ON PERCENT
REDUCTION IN AREA AND PERCENT ELONGATION FOR HEATS A AND B PLATE
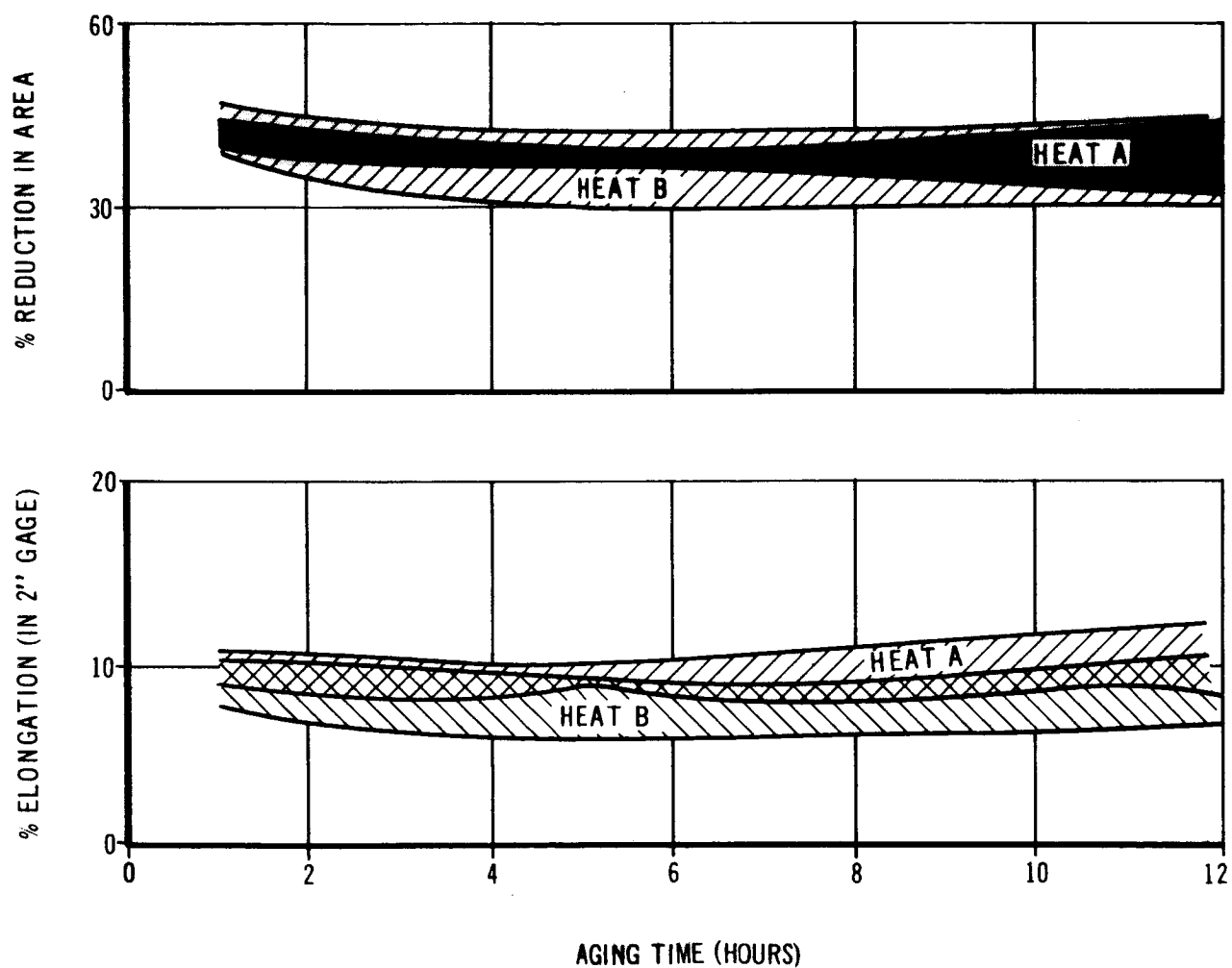
FIGURE 25

EFFECT OF AGING TEMPERATURES AND TIME ON HARDNESS FOR HEATS 1, A AND B PLATE

FIGURE 26

47
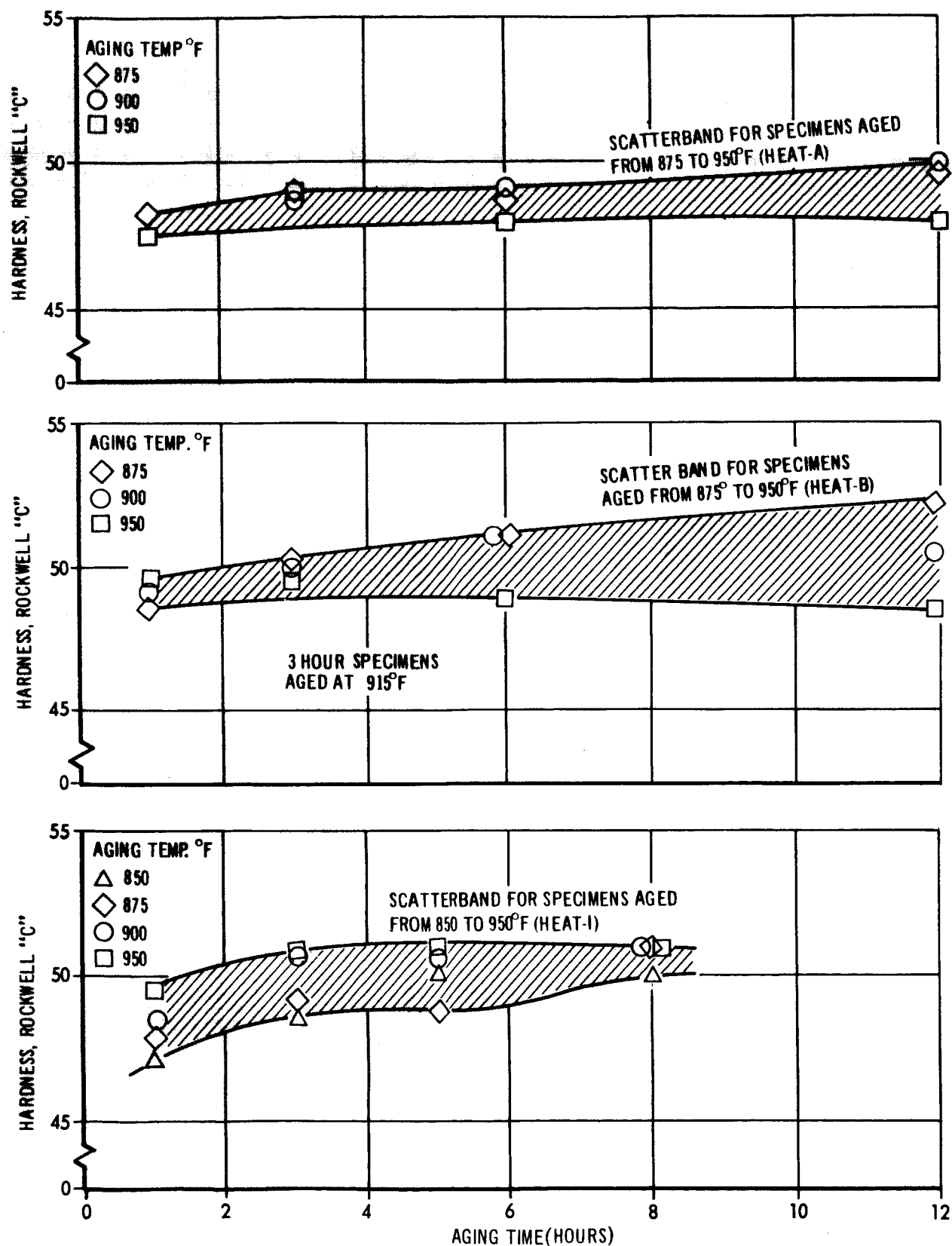
2.8   Fracture Toughness of Plate

This section describes the plane strain fracture toughness properties of plate from the three heats. All results discussed in this section pertain to full thickness plate specimens. Results obtained using a subsize specimen are discussed in a subsequent section, wherein specimen size effects are described.

Heat I plate was evaluated using the 48-in PTC test specimen (Figure 7) exclusively, and only in the longitudinal (parallel to the rolling) direction. One aging temperature (900°F) and two aging times (3 and 12 hours) were evaluated. Heat A and B plates were evaluated using the 24-in specimen (Figure 8). Heat A plate was tested after 900°F, 3 hour aging only. Two aging temperatures (875°F and 900°F) and two aging times (3 and 12 hours) were employed for Heat B. Longitudinal and transverse specimens were tested for Heats A and B plate. The dependence of net-fracture stress on shallow-crack depth was studied. (Crack depth, rather than length or some other crack-shape parameter, was selected as the independent variable. However, it should be recognized that depth may not be the most significant crack-shape parameter. Studies are currently in progress at Douglas to define the most significant crack-shape parameter). Net stress is calculated on the basis of original crack size as displayed on the fracture surface. The area is calculated from length and depth measurements by assuming the crack to be a semi-ellipse. Figure 27 illustrates the excellent agreement between calculated and actual area for several specimens. The actual area was determined by a planimetric

2.8   <u>Fracture Toughness of Plate</u> (Cont'd.)

measurement of a photographically enlarged image of the crack on
the fracture surface. The results for the three plate heats are
discussed in the following three paragraphs. Tabulated data,
including crack depth and length, are presented in Appendix V.

2.8.1   <u>Heat I</u>

The results depicted in Figure 28 show that the net-fracture stress
of Heat I plate, after 3 hour aging at 900°F, remains constant until
a crack depth of approximately 0.110 inches (the "critical depth")
is reached. Thereafter, the net-fracture stress decreases steadily
with increasing crack depth. Similar behavior is observed after a
12 hour age. However, the critical crack depth after 12 hours may
be somewhat less (perhaps as low as; 0.080-in; however, the data are
not decisive). The net stress for a given crack depth is 10 to 20
KSI less after 12 hour aging than it is after 3 hours.

2.8.2   <u>Heat A</u>

Heat A data exhibit very close agreement with that for Heat I plate
aged for 3 hours. The longitudinal properties of Heat A may be
slightly superior to those for Heat I, but the differences appear
to be small. The transverse properties of Heat A plate appear to be
somewhat inferior to the longitudinal properties. This may be
ascertained by comparing the net-fracture stresses for approximately
identical crack sizes.

2.8.3   Heat B

Figure 29 illustrates the net fracture stress dependence on crack depth after 12 hour aging at 875°F. Figure 30 presents the dependence after 3 and 12 hour aging at 900°F. Both longitudinal and transverse orientations are depicted. The behavior is similar to that observed for Heats I and A plate. Notably, however, the critical crack depth is less, ranging from about 0.050 inches to 0.075 inches. As in the cases of Heats I and A plate, both the critical crack depth and the net-fracture stress (for a given crack depth) appear to decrease upon extended aging treatment.

2.8.4   Plane Strain Fracture Toughness Parameter, K_{IC}

Plane strain fracture toughness values, K_{IC}*were calculated from Irwin's equation (Reference 1), as follows:

$$K_{IC} = \sqrt{\frac{3.77\sigma^2 \, b}{\emptyset^2 - 0.212 \left(\frac{\sigma}{\sigma_{YS}}\right)^2}}$$

where,

$$\emptyset = \int_{\theta = 0}^{\theta = \pi/2} \sqrt{1 - \left(\frac{a^2 - b^2}{a^2}\right) \sin^2\theta} \; d\theta$$

* K_{IC} is an analytically derived expression related to a material's resistance to premature failure in the presence of a flaw. For a given tensile strength level, resistance to failure is directly proportional to K_{IC}.

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2.8.4   Plane Strain Fracture Toughness Parameter, K_{IC} (Cont'd.)

    2a = Crack length

    b = Crack depth

    σ = Gross-fracture stress

    $\sigma_{y.s}$ = 0.2% offset yield strength

The following sections pertain to the dependence of K_{IC} on thermal treatments and orientation.

2.8.5   Effect of Aging Duration and Temperature on K_{IC}

Figure 31 presents a bar chart depicting the spread in K_{IC} for the various aging treatments evaluated. Tabulated values are presented in Appendix V. The results show that transverse properties are somewhat inferior to longitudinal, and that prolonged aging tends to degrade K_{IC}. Heat I plate exhibits the latter trends most markedly. (As will be seen in subsequent sections, the differences attributable to specimen size are inconsequential.)

2.8.6   Comparison of Experimental and Theoretical Dependence of Fracture Stress on Crack Size

Figure 32 illustrates the comparative net fracture stress versus crack depth dependencies for both experimental data (Heat B plate) and theoretical curves derived from Irwin's equation. The theoretical curves (calculated using $\sigma_{y.s.}$ = 280 KSI and K_{IC} = 98 KSI $\sqrt{in}$) are depicted for a range of crack length-to-depth ratios from two to eight. The theoretical curves are extrapolated to intersection with the ultimate strength plateau so as to approximate critical

RELATIONSHIP BETWEEN MEASURED CRACK AREA, AND CALCULATED CRACK AREA
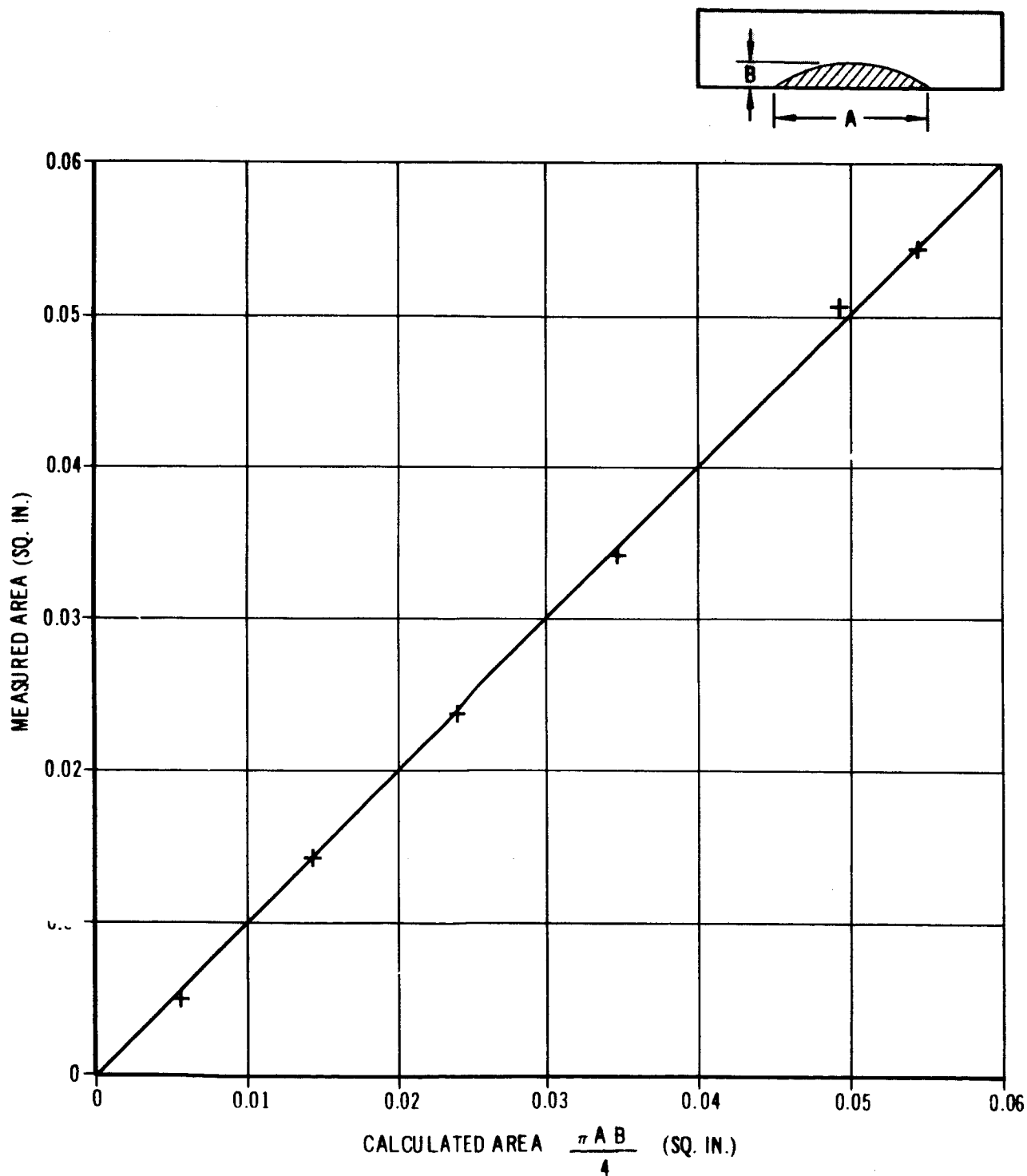
FIGURE 27

EFFECT OF CRACK DEPTH ON THE NET FRACTURE
STRESS OF 3/4 IN. THICK AIRMELTED 18Ni-7Co-5Mo PLATE
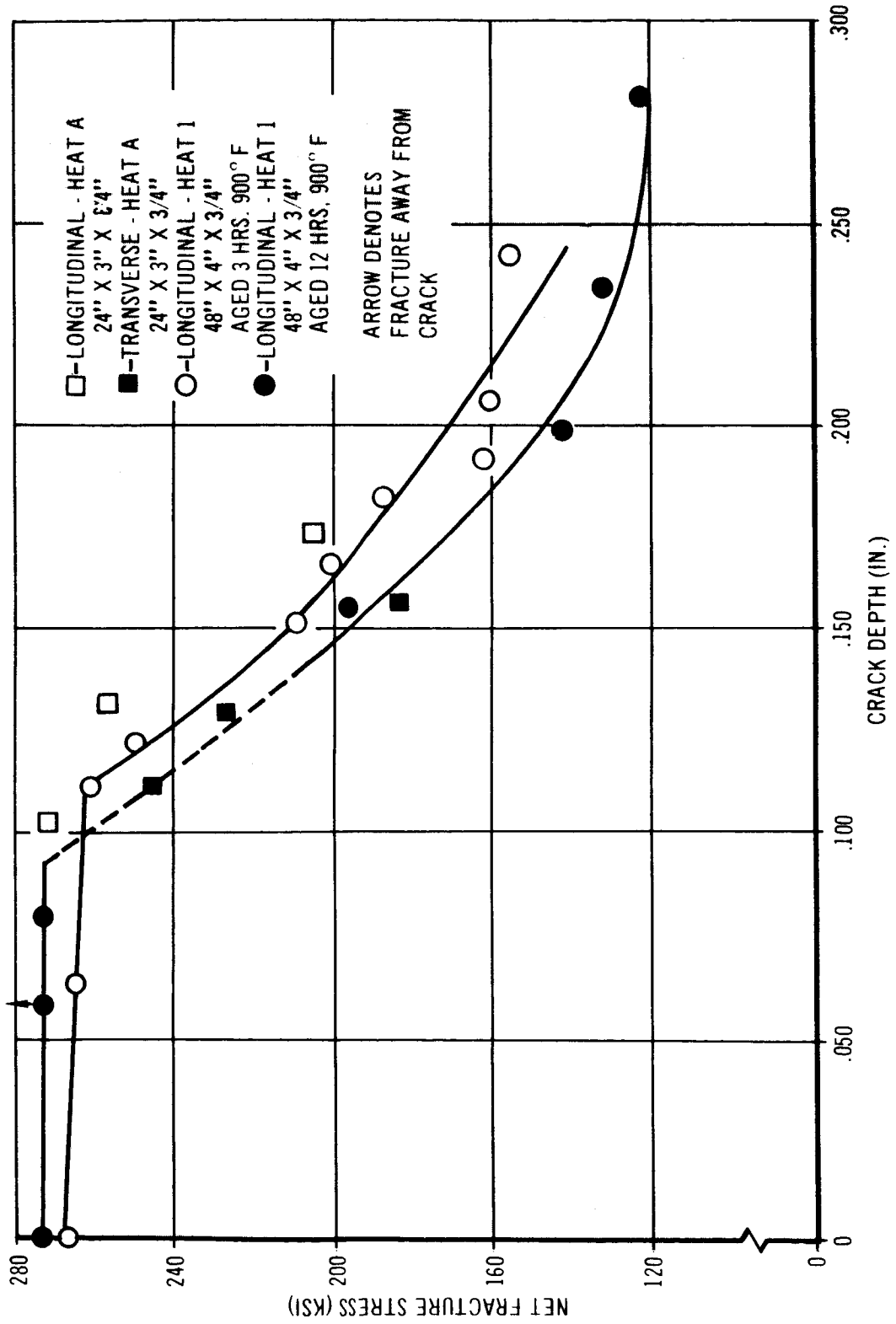
FIGURE 28

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EFFECT OF CRACK DEPTH ON
THE NET FRACTURE STRESS OF
HEAT-B

18 Ni-7 Co-5 Mo PLATE

24" × 3" × ¾" SPECIMENS
875°F, 12 HR.
⊙ – LONGITUDINAL
● – TRANSVERSE

CRACK DEPTH (IN.)

NET FRACTURE STRESS (KSI)

FIGURE 29

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EFFECT OF CRACK DEPTH ON THE NET
FRACTURE STRESS OF HEAT-B
18 Ni-7 Co-5 Mo PLATE

24" × 3" × ¾" PTC SPECIMENS
○ – 900, 3 HR.
◇ – 900, 12 HR.
OPEN SYMBOLS – LONGITUDINAL
SOLID SYMBOLS – TRANSVERSE

NET FRACTURE STRESS (KSI)

CRACK DEPTH (IN.)

FIGURE 30

55
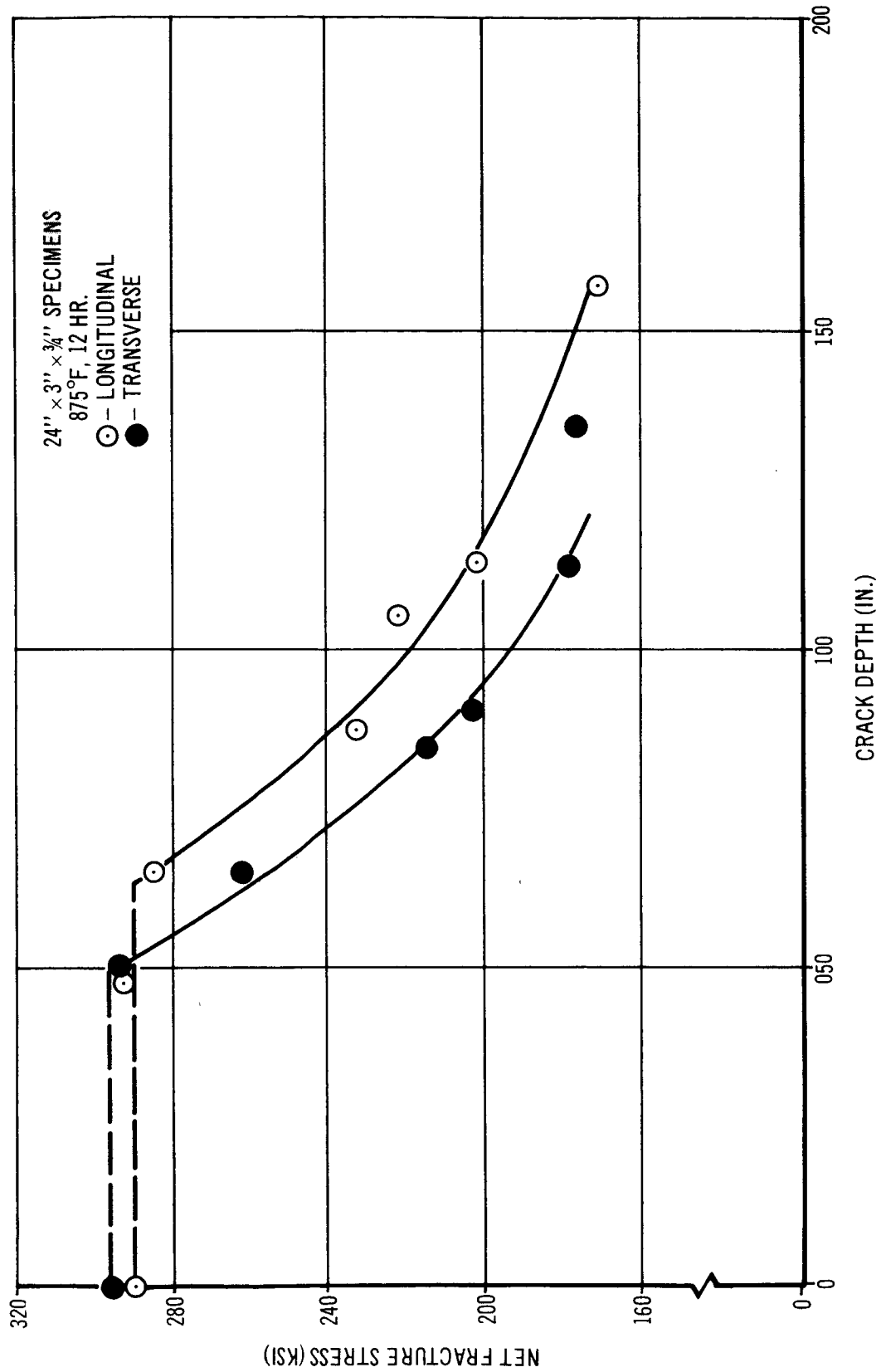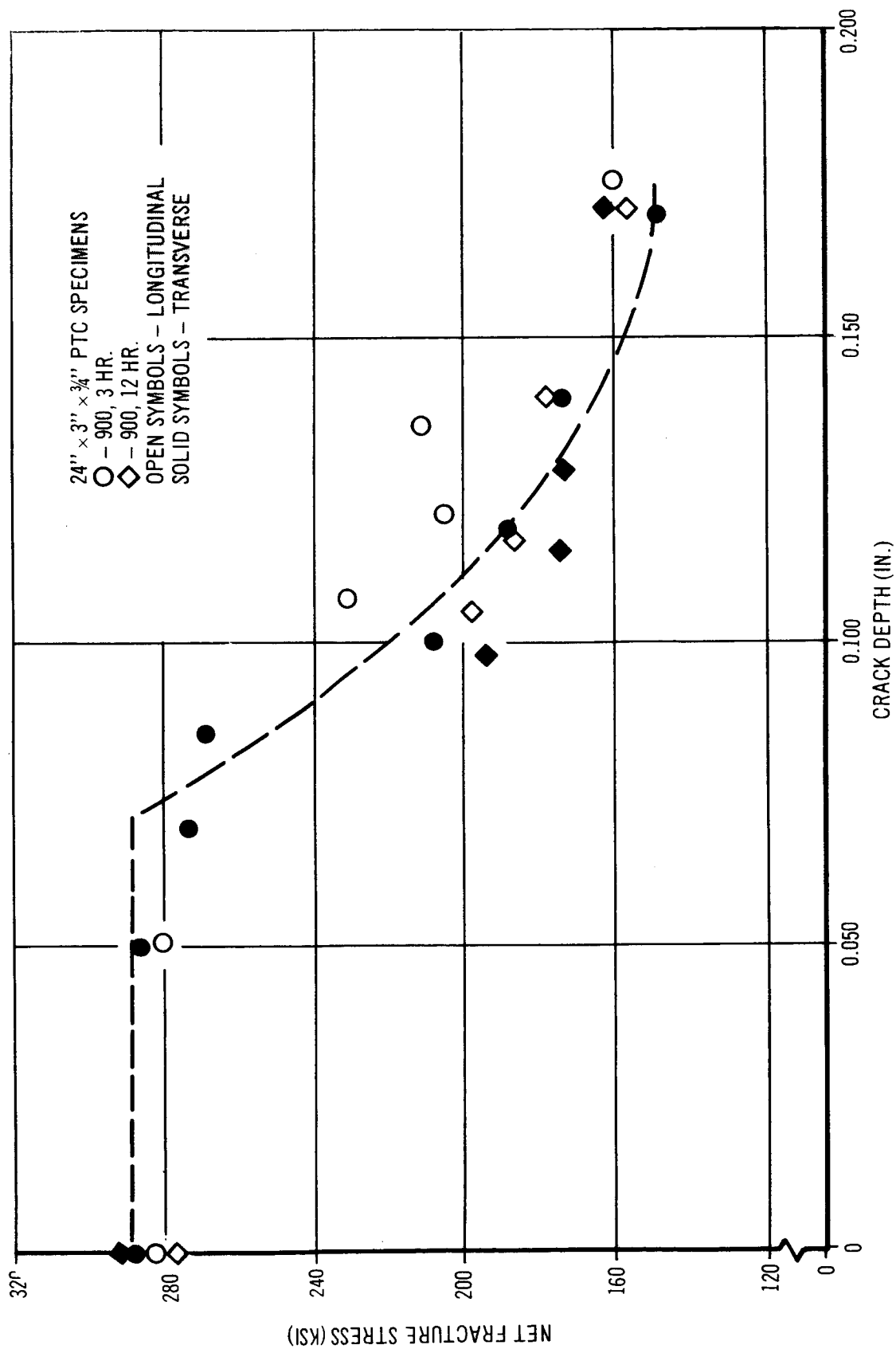
EFFECT OF AGING HEAT TREATMENT ON K_{IC}
OF THE THREE PLATE HEATS
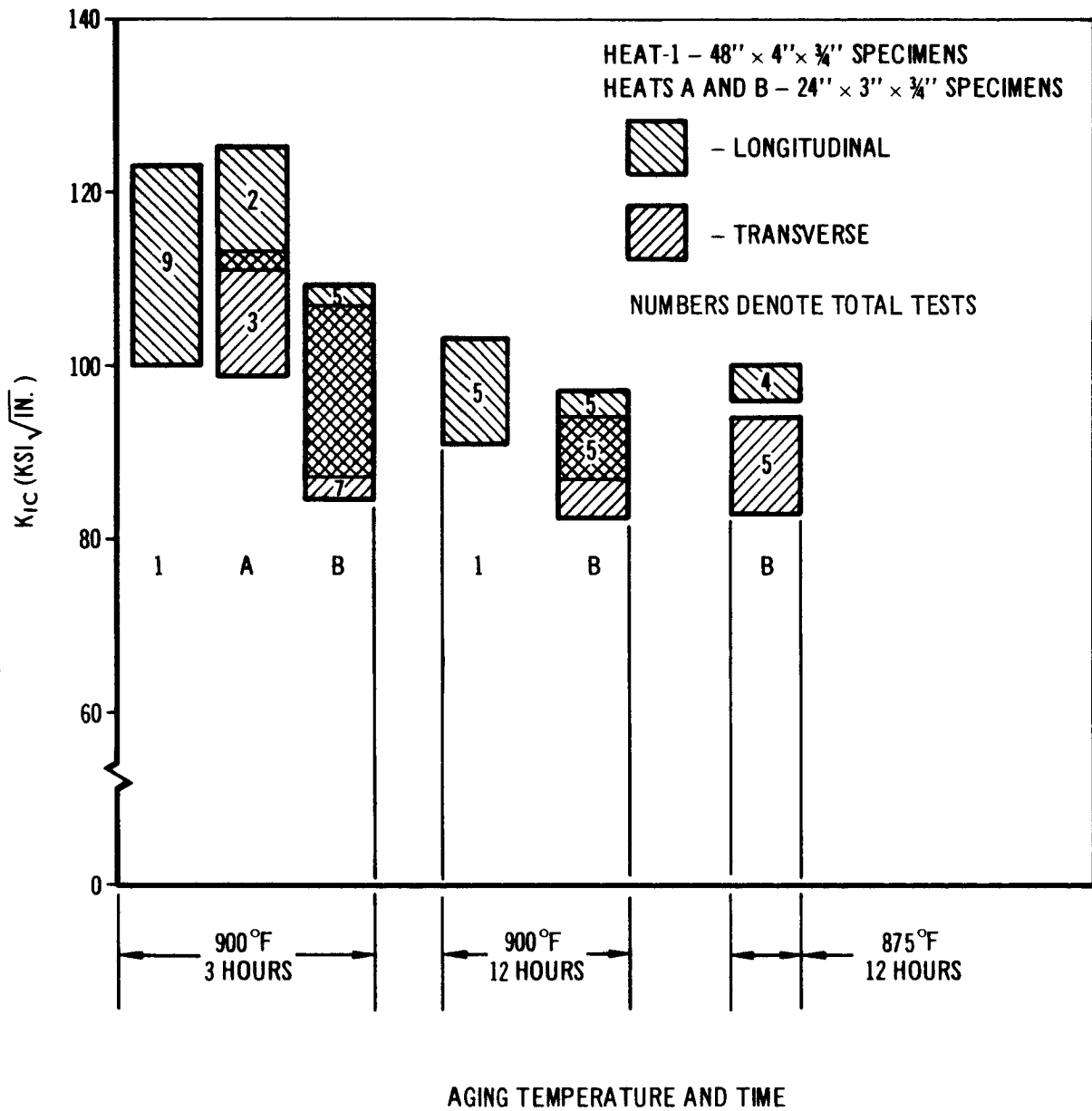
FIGURE 31

2.8.6   <u>Comparison of Experimental and Theoretical Dependence of Fracture</u>
         <u>Stress on Crack Size</u> (Cont'd.)

         crack depths. Since the 18Ni-7Co-5Mo plate under study is

         characterized by yield-to-ultimate strength ratios exceeding 0.9,

         such an extrapolation is not unreasonable.

         The experimental data fall within the calculated theoretical range

         (i.e, 2a/b equal from about 2 to 4). The actual critical crack

         depth range is reasonably approximated by the intercept of the

         theoretical curve for 2a/b = 2 with the ultimate strength plateau.

         However, such approximations may not always be accurate enough for

         process control requirements. Nonetheless, these data demonstrate

         that theoretical plane strain fracture toughness values may portray

         the actual behavior with reasonable accuracy. More comprehensive

         comparisons are necessary to fully establish the generality of the

         theoretical correlations with experimental data.

2.9   <u>Evaluation of Small PTC Specimen</u>

         The measurement of plane strain fracture toughness of high-strength

         alloys has been approached in many ways. Generally, if edge-cracked

         or center-cracked specimens (References 2 and 3) are used, rather

         expensive and elaborate techniques are required for the determination

         of the onset of rapid crack propagation. The partial thickness

         crack specimen (References 1 and 4) now commonly designated as the

         PTC specimen, has the virtue of being much simpler to test and to

         analyze. Perhaps even more important is the fact that this test

         yields information (i.e., net-fracture stress versus crack size)

COMPARISON OF EXPERIMENTAL AND THEORETICAL
DEPENDENCE OF FRACTURE STRESS ON CRACK SIZE

APPROXIMATE RANGE
OF EXPERIMENTAL
DATA FOR HEAT-B PLATE
(24" ×3" ×¾" PTC SPECIMENS
2a/b = 2 TO 3 AGED 900°F, 3 HRS.)

THEORETICAL FOR 2a/b = 2

2a/b = 4

2a/b = 8

NET FRACTURE STRESS (KSI)

280

240

200

CRACK DEPTH, b(IN.)

0.050

0.100

0.150

0

2a

b

FIGURE 32

58
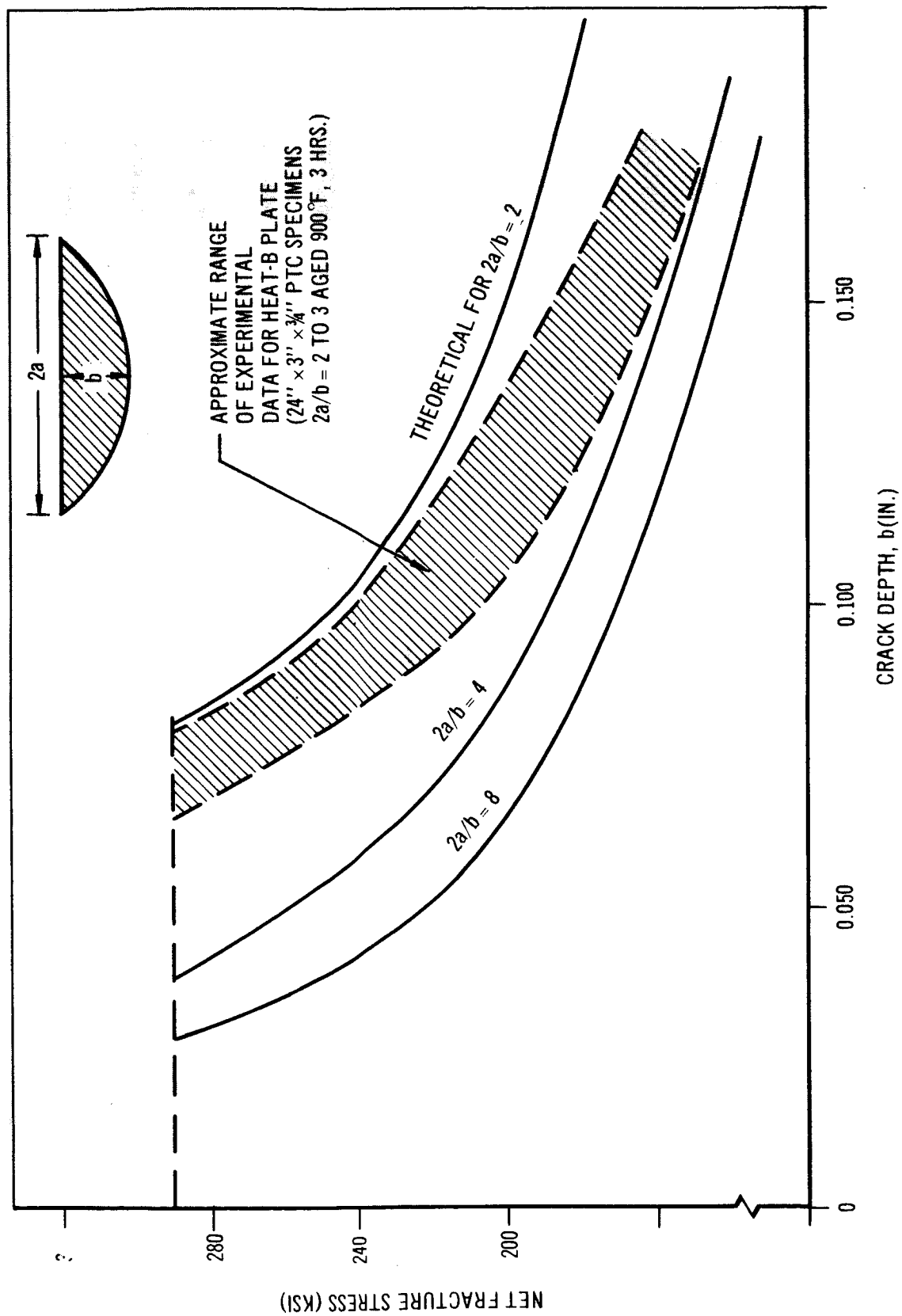
2.9   Evaluation of Small PTC Specimen

which may be used directly for design and inspection purposes.
Also plane-strain fracture toughness values, K_{IC}, may be directly
calculated from the results using Irwin's analysis assuming
negligible slow crack extension. The latter assumption is often
questioned; however, sustained load data presented later show that
this assumption, at least for these maraging alloys, is reasonable.

The PTC test has often been objected to, however, because of the
belief that large specimens were required to obtain valid results.
Data presented in this section provide the justification for the
use of a small, economical, plane strain PTC specimen.

2.9.1   Background

During the initial stages of the 18Ni-7Co-5Mo maraging steel in-
vestigations at Douglas, the large 48" x 4" x 3/4" specimen was
employed to measure the fracture toughness of the 3/4-inch thick
plate and welds (Figure 7). Obviously, this specimen consumed
much material, was expensive from the standpoint of machining and
testing, and because of its weight (108 lb) was rather difficult to
handle. Testing of welds with this type of specimen further
requires a one foot long weld for each specimen (assuming a
transverse test), which thus pyramids the cost of gathering
sufficient data needed for research-type investigations. For the
latter reasons, and based on earlier data on AISI 4340 (Reference 5),
a small PTC specimen was evaluated for welds (Figure 33). Figure 34
compares results obtained with the two specimen types in evaluating

2.9.1 Background (Cont'd.)

the fracture toughness of weldmetal (Reference 7). (Discussions concerning welding procedures and compositional effects are presented in a later section.) The results indicate rather close correlation between the two specimen sizes. It should be noted that the ratio of crack length to depth is about the same for the two PTC specimens sizes (length = 2 1/2 to 3 x depth). Otherwise, such good agreement would not be expected.

On the basis of the weld test results, a far more comprehensive evaluation of the effects of specimen size was undertaken on Heat B plate using the configurations illustrated in Figures 8 and 9. One specimen, the 24" x 3"x 3/4", was used to test full plate thickness with the crack plane perpendicular to the plate surface (results described previously). The orientations used for the 8" x 11/16" x 5/16" specimens are illustrated in Figure 35. The geometry of the latter specimen was selected on the basis that the largest crack to be tested would not exceed one-half the specimen thickness (thus fulfilling Irwin's criteria for K_{IC} calculations). The small 8" x 11/16 x 5/16" PTC specimens were subjected to aging treatments identical to those investigated for the previously discussed 24" x 3" x 3/4" PTC specimens.

2.9.2 Effect of Specimen Size and Orientation on Net Fracture Stress

To fully compare the 8-in PTC specimens with the larger type, specimens were removed in the three orientations shown in Figure 35. Two are designated "thickness" types, and are the most economical

to machine.   The specimens were all aged at a constant temperature (900°F) for two different times (3 hours, 12 hours).

Examination of the net fracture stress data, illustrated in Figure 36, shows that substantially the same results are obtained with the three specimen configurations. The results obtained with surface-type 8" PTC correlate closer with the 24" PTC specimen that with the results from the thickness-type 8" specimen. This might have been anticipated since the crack propagation direction for the 8" PTC surface type and 24" PTC specimens coincides.

The principal crack propagation direction for the thickness-type 8" x 11/16" x 5/16" specimen is 90 degrees to that for the surface type (i.e., approximating short transverse). Thus, the differences that are seen apparently reflect this orientation difference rather than that of specimen geometry. Generally, the data from the 8" are slightly more conservative than those from the 24" specimens. (Tabulated data for the 8-in specimens are presented in Appendix VI). The good agreement between the two specimen geometries would not have been expected had not the crack elipticity ratio (crack length-to depth ratio) been about the same. Figure 37 illustrates the relative constancy of the elipticity ratio for a variety of the two specimen types (welds are also included and will be discussed in detail later).

SHALLOW CRACK FRACTURE TOUGHNESS TEST SPECIMEN

8" × 1/2" × 1/8

1/2" TO 3" RAD (TYP)

t 0.130 ± 0.005"

2-1/2"

1-1/4"

W .500 ± .010"

11/16 ± 1/16"

8"
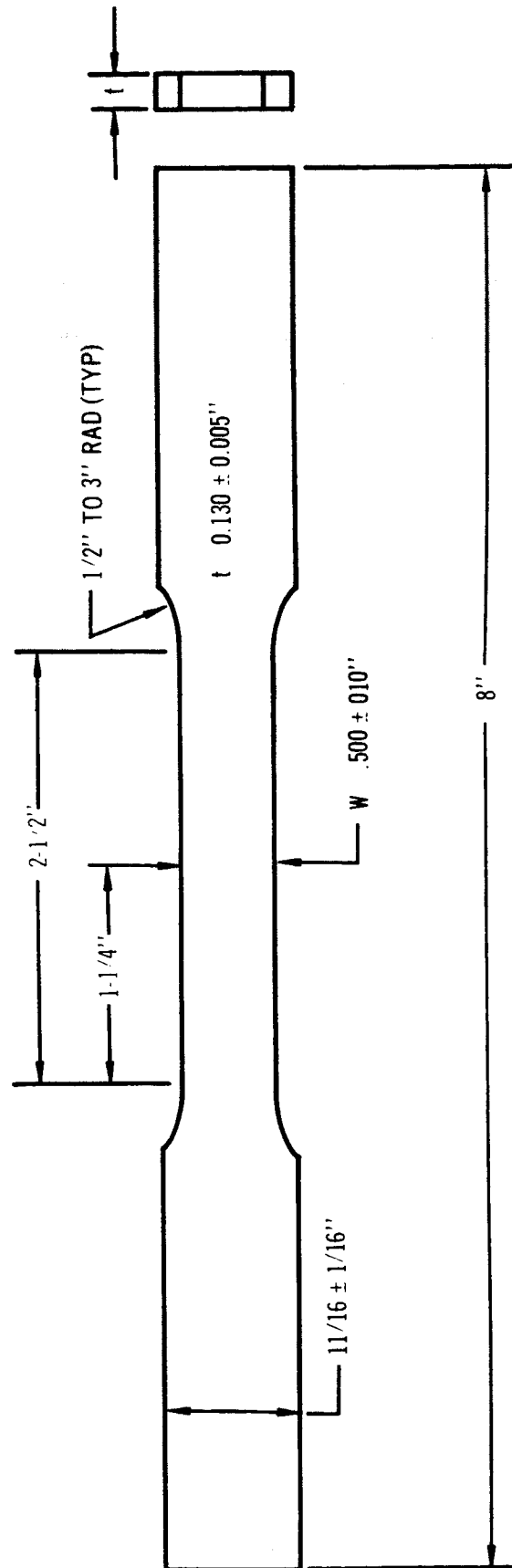
FIGURE 33

FRACTURE STRENGTH VS CRACK DEPTH
TYPE W2 WELDS IN 3/4" 18 Ni-7 Co-5 Mo
AIRMELTED PLATE

900F, 12 HRS
MIG WELDS
HEAT-1 PLATE

△ 8" X 1/2 X 1/8" PTC SPECIMENS
▲ 48" X 4 X 3/4" PTC SPECIMENS

NET FRACTURE STRESS (KSI)
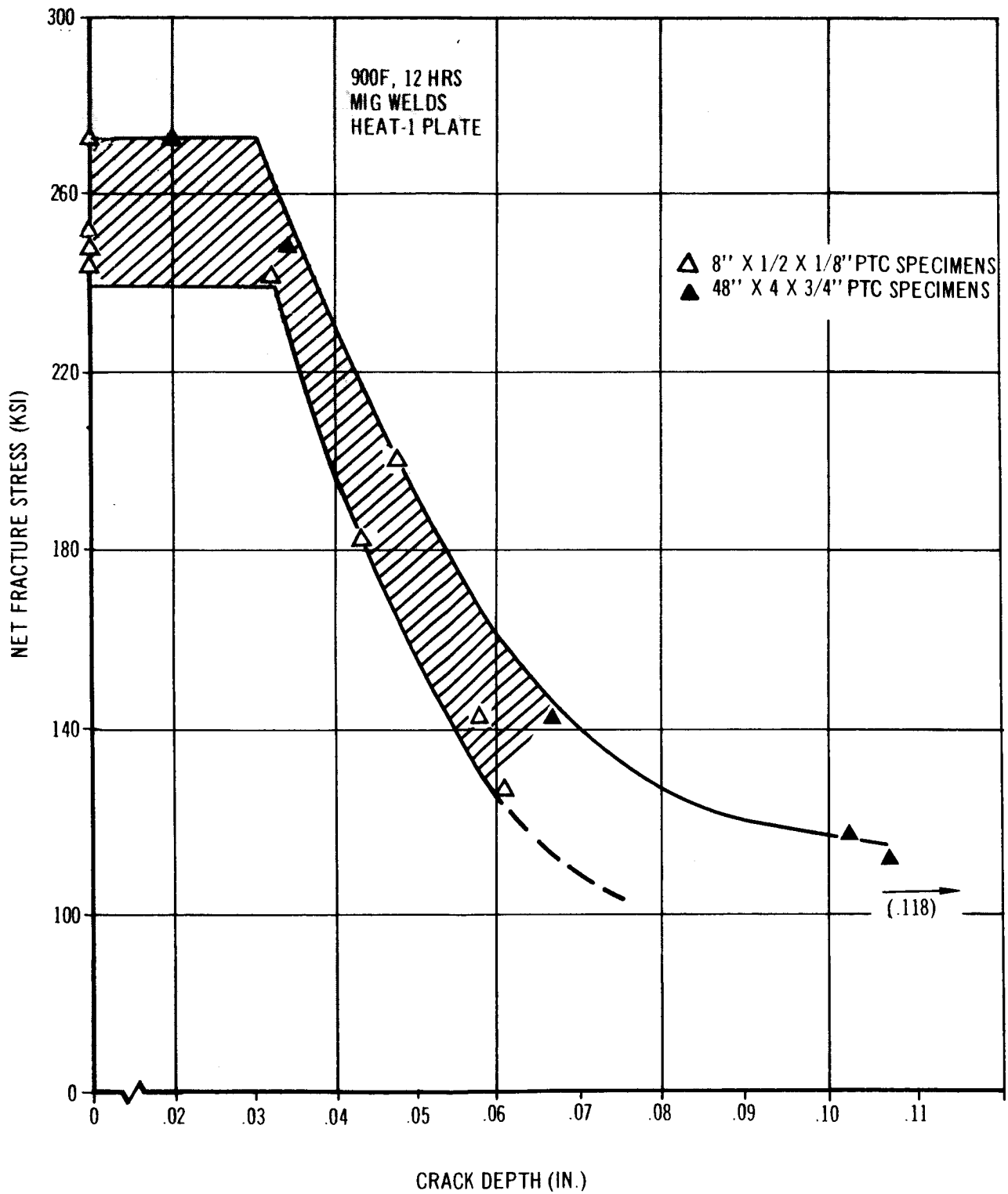
CRACK DEPTH (IN.)

FIGURE 34

ORIENTATIONS OF THE 8" X 11/16" X 5/16" PARTIAL THICKNESS CRACK SPECIMEN

SURFACE TYPE

3/4

ROLLING DIRECTION

THICKNESS TYPE

PARTIAL THROUGH CRACK

11/16

5/16
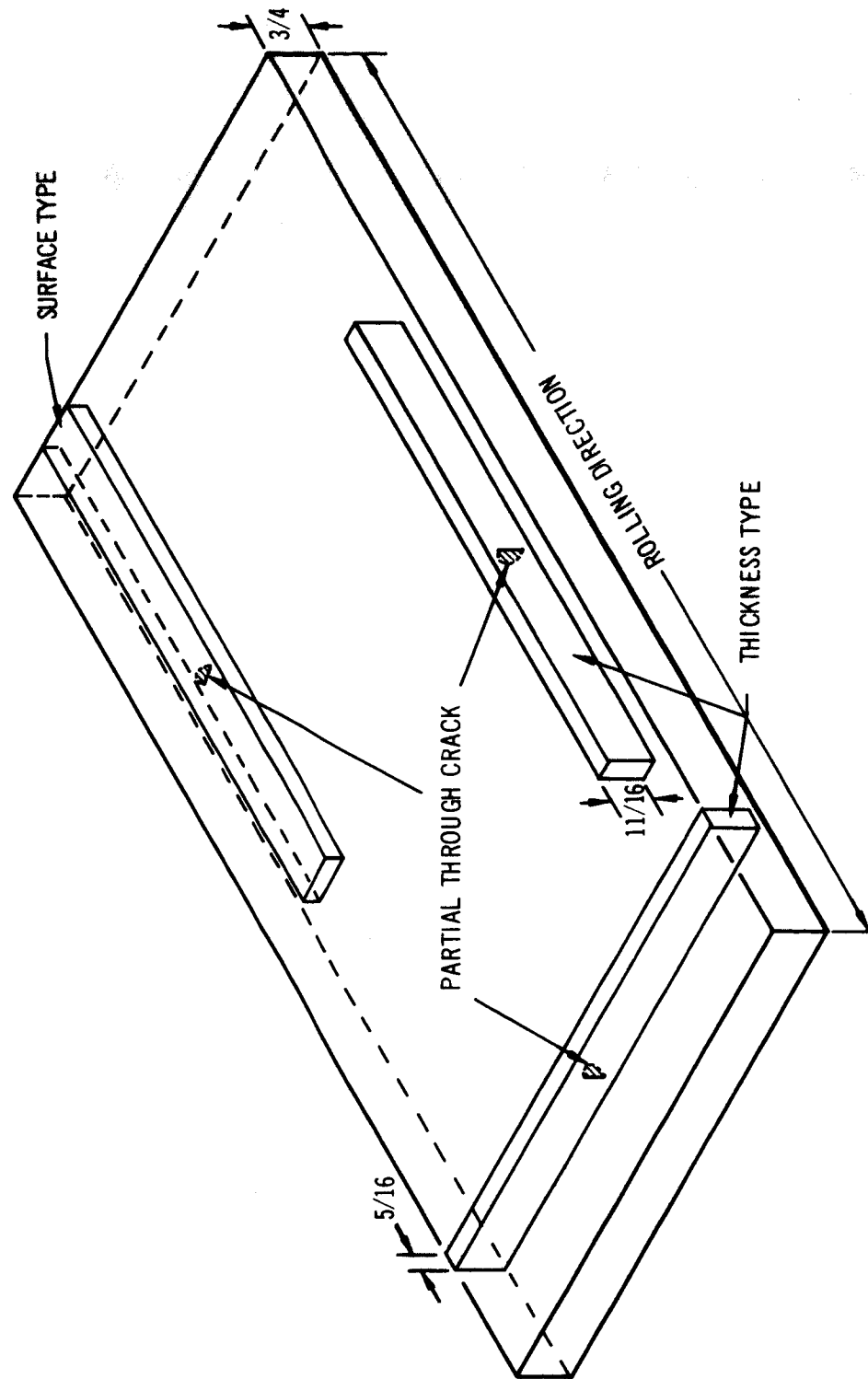
FIGURE 35

EFFECT OF CRACK DEPTH ON NET FRACTURE STRESS FOR TWO SPECIMEN CONFIGURATIONS, SEVERAL ORIENTATIONS AND AGING TREATMENTS - HEAT B PLATE

⊙ 24" X 3" X 3/4" - 875° F 12 HRS LONG
◯ 8" X 11/16" X 5/16" - 900° F 12 HRS LONG - (THICKNESS TYPE)
▽ 24" X 3" X 3/4" - 875° F 12 HRS TRANS
◇ 8" X 11/16" X 5/16" - 900° F 12 HRS -TRANS (THICKNESS TYPE)
△ 8" X 11/16" X 5/16" - 900° F 3 HRS LONG - THICKNESS TYPE)
□ 8" X 11/16" X 5/16" - 900° F 3 HRS TRANS - (THICKNESS TYPE)
■ 24" X 3" X 3/4" - 900° F 3 HRS TRANS
▲ 24" X 3" X 3/4" - 900° F 3 HRS LONG
◆ 24" X 3" X 3/4" - 900° F 12 HRS TRANS
● 24" X 3" X 3/4" - 900° F 12 HRS LONG
△ 8" X 11/16" X 5/16" - 900° F 3 HRS LONG - (SURFACE TYPE)

FIGURE 36

65
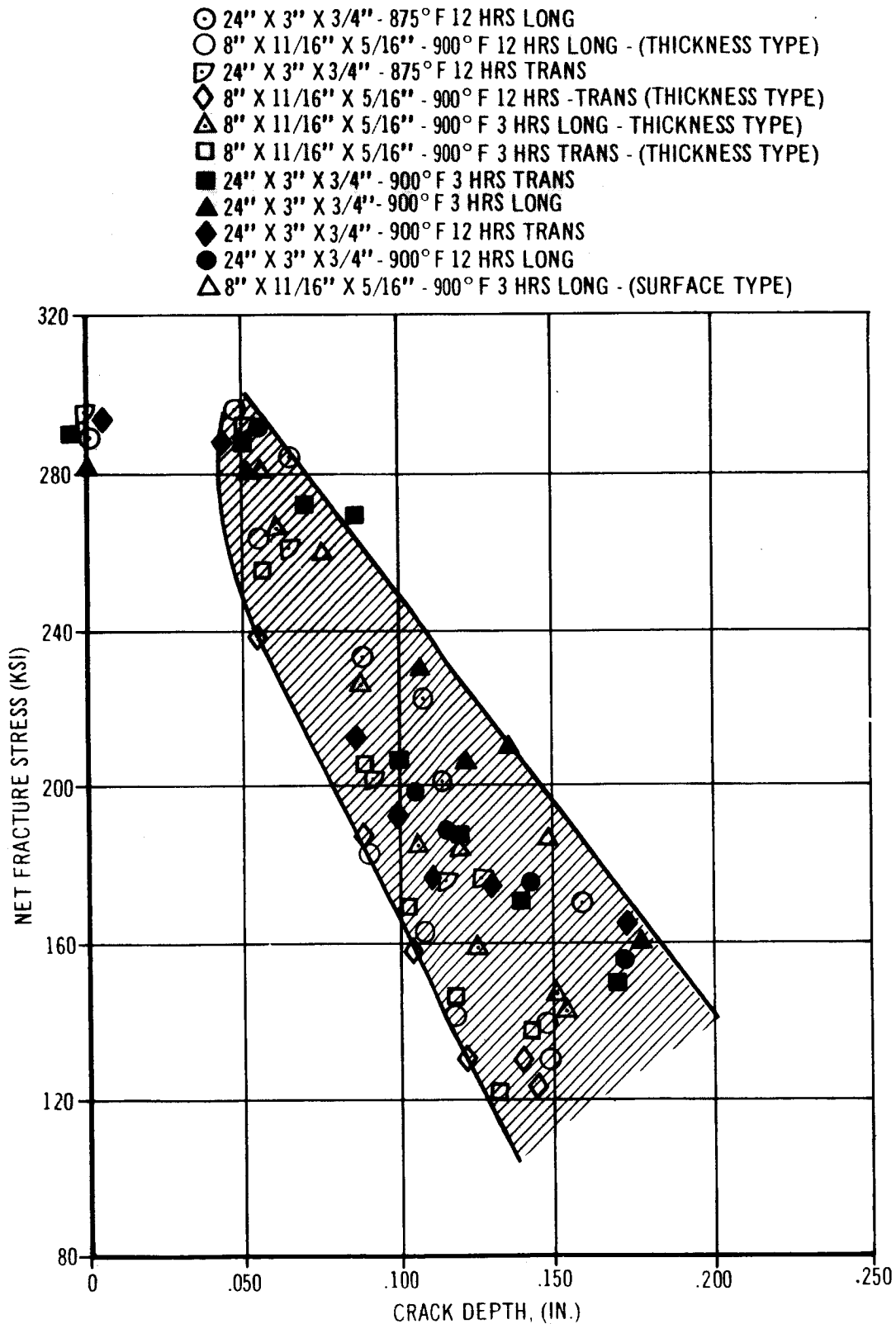
RELATIONSHIP BETWEEN CRACK LENGTH
AND DEPTH IN PARTIAL THICKNESS CRACK SPECIMENS

FIGURE 37

66
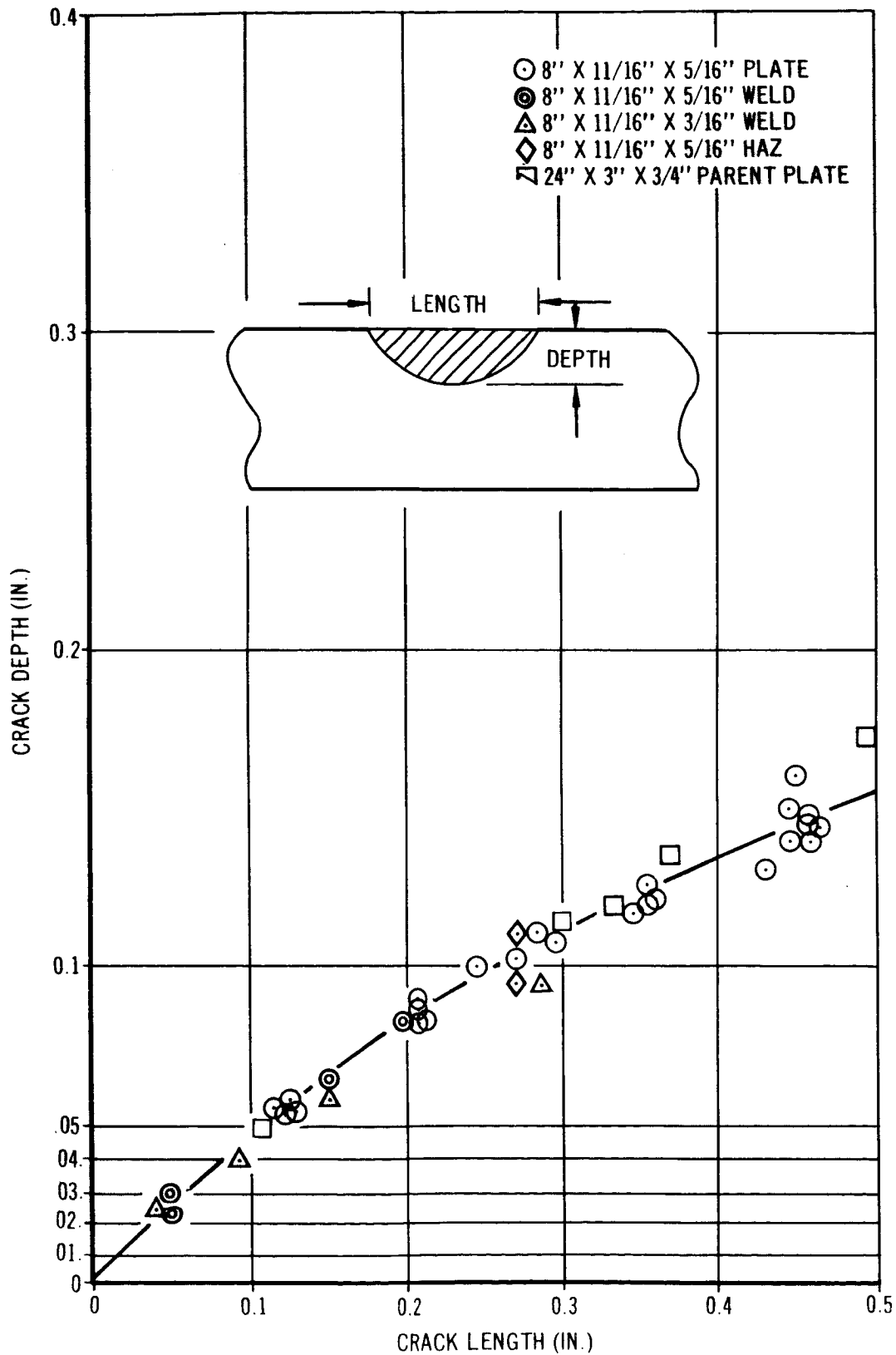
2.9.3   Effect of Specimen Size on K_{IC}

The calculation of K_{IC} from the data generated using the 8-in. PTC specimens presented a special problem. In the case of these specimens, the area occupied by the partial thickness crack was a relatively substantial fraction (approaching 30 per cent for the largest cracks) of the total cross sectional area of the specimen. Partial thickness cracks in the 24-in. specimens occupied a relatively negligible area fraction of the total cross section. Therefore, the calculation of K_{IC} for the 8-in. specimens on the basis of gross stress resulted in a geometrically induced bias. In an effort to overcome this geometrical bias, "quasi" K_{IC} values were also calculated on the basis of net, rather than gross, fracture stress. Net stress represents a convenient, albeit arbitrary, weighting function which tends to compensate for the geometry effects. Obvious theoretical justification for the use of net fracture stress in the K_{IC} equation is lacking.

Figure 38 illustrates the result of the net stress correction on K_{IC} (complete tabulations of K_{IC} calculations based on net and gross fracture stress are presented in Appendix VI). The figure illustrates the effects of calculating K_{IC} from gross and net stress for the surface type 8-in PTC specimens (longitudinal, aged 900°F, 3 hours). Results for identically treated 24-in. PTC specimens are shown for comparison. The data demonstrate that the net stress weighting function brings the K_{IC} values for the 8-in and 24-in. specimens into approximate equivalence (as expected since orientations are identical). Furthermore, for the crack size range

evaluated, K_{IC} becomes relatively constant. (However such constancy would not have arisen had not the crack length-to-depth ratios been virtually constant and identical for both specimen sizes). The data shown in Figure 38 are characteristic of the remainder of the data tabulated in Appendix VI.

A comprehensive comparison of the 8-in and 24-in specimens is given in Figure 39 on the basis of K_{IC} versus the ratio of total cross-sectional area to net cross-sectional area. This ratio represents a convenient parameter of the relative size of the crack and specimen cross sectional area and is in fact equivalent to the ratio of net-fracture stress to gross-fracture stress. K_{IC} was calculated on the basis of net fracture stress for all the 8-in specimens. A direct comparison of the two specimen configurations can be made by symbols without tails (24") to like symbols with tails (8"). The "surface" type coupons correlate closer to the 24-in coupons, than the "thickness" type. Maximum differences of about 10 percent are seen. The 8-in "thickness" type specimens exhibit somewhat lower K_{IC} values than the "surface" type, but as reported in a previous section, this might be expected.

The small specimens tend to favor the right side of the graph. This trend is due to the dependence of the ratio of net stress to gross stress on specimen size. For the 24-in specimens, the net and gross stresses are very nearly equivalent, while for the 8-in specimens substantial differences exist. Relative size differences are illus-

2.9.3   Effect of Specimen Size on K_{IC} (Cont'd.)

trated in Figure 40. Regardless of the value of the ratio, the K_{IC}
values are in good agreement for both types of specimens. Especially
good agreement persists when crack propagation directions are
identical.

The results show that plane strain K_{IC} values and net fracture stress
data generated using either specimen are substantially the same.
From the standpoint of economics, the 8-in "thickness" type specimen
is favored even though the values obtained are somewhat more con-
servative than those obtained from the 24-in. specimens. On the
basis of these results, the 8" x 11/16" x 5/16" PTC specimen was
used extensively for the weld studies to be described in the forth-
coming sections.

The approach represented by these results should not be generalized
for all alloys unless specifically demonstrated to be applicable.
Theoretical analysis of specimen geometry and relative crack size
effects are also required.

2.9.4   Fracture Surface Appearance

Figure 41 illustrates the fracture surfaces typical of transverse
and longitudinal 24-in PTC specimens from Heats A and B plate. The
transverse specimens exhibit surfaces characterized by striations
parallel to the rolling direction. Striations are far less prevalent
on the fracture surfaces of the longitudinal specimens. The
striations are probably related to the banded microstructure

EFFECT OF K_{IC} METHOD OF CALCULATION ON THE DEPENDENCE OF
K_{IC} ON CRACK SIZE FOR 8-IN AND 24-IN. PTC SPECIMENS

8" × 11/16 × 5/16" PTC SPECIMEN
⊙ K_{IC} CALCULATED FROM GROSS STRESS
● K_{IC} CALCULATED FROM NET STRESS

24" × 3" × 3/4" PTC SPECIMEN
△ K_{IC} CALCULATED FROM GROSS STRESS

HEAT-B PLATE, LONGITUDINAL SPECIMENS
900°F, 3 HR

CRACK DEPTH, IN

K_{IC}(KSI $\sqrt{}$ IN)

FIGURE 38

70
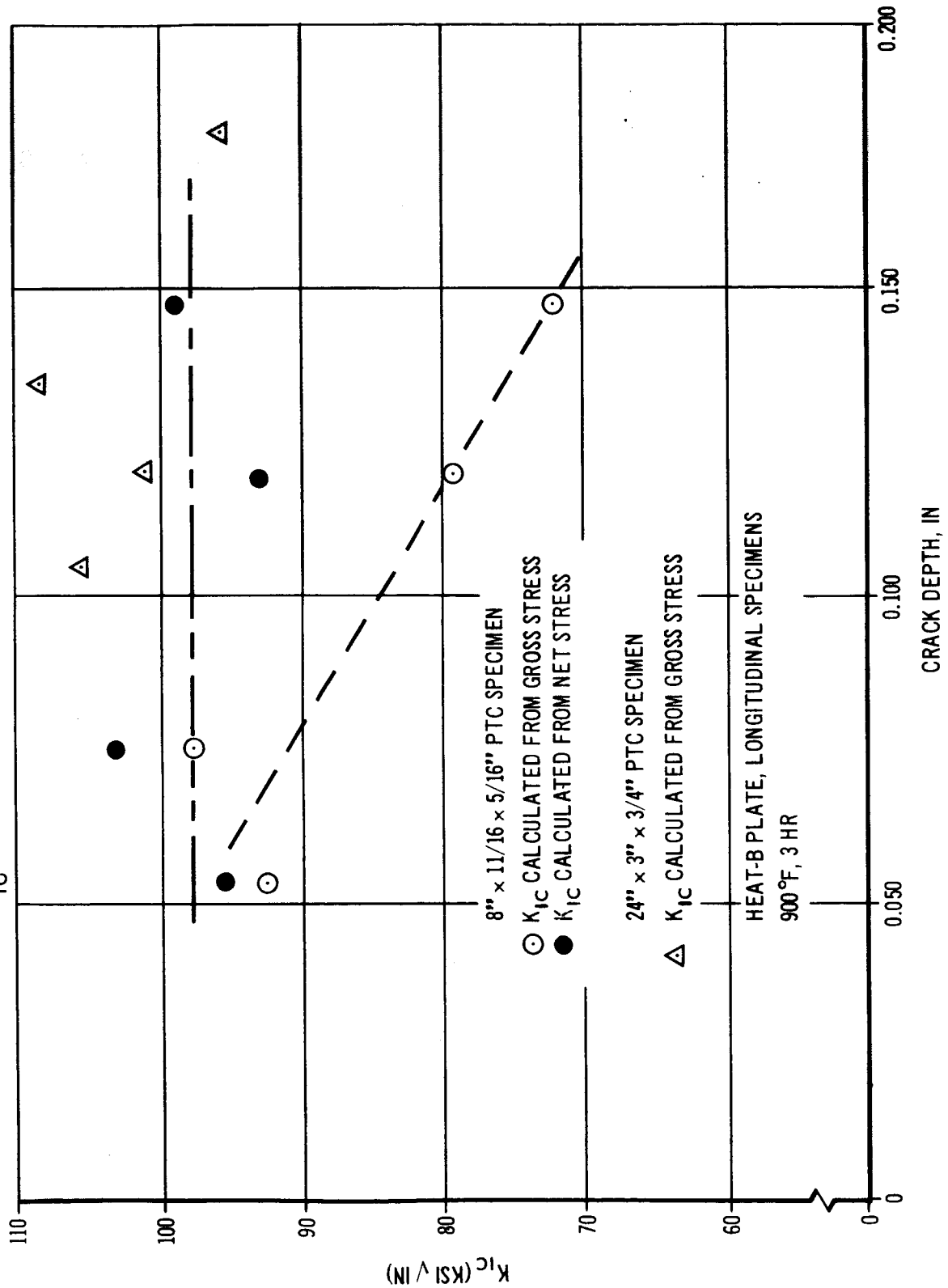
EFFECT OF RELATIVE CRACK AREA, SPECIMEN
ORIENTATION AND AGING TREATMENT ON K$_{IC}$
HEAT - B PLATE

TOTAL CROSS-SECTIONAL AREA
───────────────────────────
NET CROSS-SECTIONAL AREA

or

NET-FRACTURE STRESS
─────────────────────
GROSS FRACTURE STRESS

● 900° F 3 HRS LONG
⊙ 900° F 3 HRS TRANS
■ 900° F 12 HRS LONG
▫ 900° F 12 HRS TRANS
▲ 875° F 12 HRS LONG
△ 875° F 12 HRS TRANS

K$_{IC}$ (KSI√IN. X 10^{-3})

SYMBOLS WITHOUT TAILS
REPRESENT 24" X 3" X 3/4"
SPECIMENS.

SYMBOLS WITH HORIZONTAL TAILS
REPRESENT 8" X 11/16" X 5/16" SPECIMENS
(THICKNESS TYPE.)

SYMBOLS WITH VERTICAL TAILS
REPRESENT 8" X 11/16" X 5/16"
SPECIMENS - (SURFACE TYPE)

FIGURE 39

71

5/16" X 11/16" FRACTURE SURFACE. CRACK LENGTH = 0.446", CRACK DEPTH = 0.143".
ELOX STARTER NOTCH AT BOTTOM IS ABOUT 0.030" LONG AND 0.015" DEEP.
FATIGUE CRACK EXTENDS UPWARD FROM LOWER SURFACE.
APPROX 8X
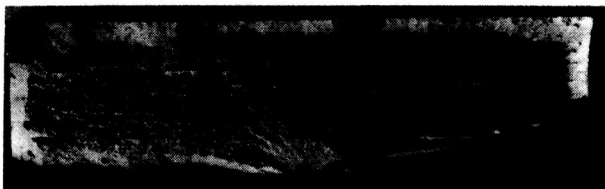
3/4" X 3" FRACTURE SURFACE. CRACK LENGTH = 0.290",
CRACK DEPTH = 0.114. ELOX STARTER NOTCH IS BARELY EVIDENT
FATIGUE CRACK EXTENDS UPWARD FROM LOWER SURFACE.
APPROX. FULL SIZE

FRACTURE SURFACE OF 8" X 11/16" X 5/16" AND 24" X 3" X 3/4"
PTC SPECIMENS ILLUSTRATING REPRESENTATIVE APPEARANCE.

FIGURE 40

2.9.4   Fracture Surface Appearance (Cont'd.)

illustrated in Figure 15. Electron fractography failed to reveal
any differences between longitudinal and transverse specimens.
However, potentially damaging inclusions were disclosed. The
significance of these inclusions and their characteristics are
described in subsequent sections.
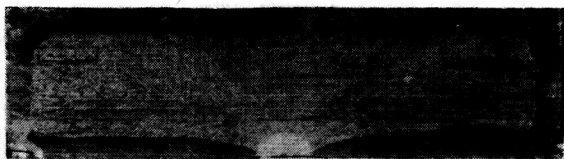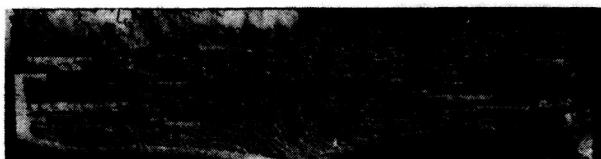
AP 4-5   P 16

TRANSVERSE

AP 4-2   P 125

LONGITUDINAL

HEAT-A   HEAT-B

MAGN.: APPROX. 1:1

TYPICAL 24'' × 3'' × ¾'' PTC FRACTURE SURFACES
HEATS-A AND B PLATE

FIGURE 41

3.   <u>PROPERTIES OF WELDED PLATE</u>

3.1   <u>INTRODUCTION</u>

The following sections present observations relating to welding
procedures and to the mechanical properties of welds deposited in
plates from Heat I and B. All data presented on welds made in
Heat I plate were acquired in the previous Douglas sponsored pro-
grams (References 5-7). All data on welds deposited in Heat B
plate were obtained from tests performed under this contract.

The majority of the welding was performed under laboratory conditions
employing flat plate specimens. However, an evaluation of welding
under simulated production conditions using special fixtures and
contoured plate segments was also undertaken.

Heat B plate welds were made by personnel at both Douglas Aircraft
Co., and Newport News Shipbuilding and Dry Dock Co. (performing as
a subcontractor). Comparison of the results obtained at the two
laboratories provides a basis for evaluating the reproducibility of
the welding procedures.

Mechanical property data on weldments include across-the-joint
tensile, all weldmetal tensile, and weldmetal and heat-affected
zone fracture toughness.

The results presented in this section relate the mechanical behavior
of weldments with respect to chemical composition, thermal treat-
ments and welding procedures. Mechanical properties and the effects
of compositional and thermal variables are in turn related, insofar

3.1   <u>INTRODUCTION</u> (Cont'd.)

as presently possible, to metallurgical observations.

3.2   <u>Flat Plate Welding - Specimen Preparation</u>

Almost all of the welding performed during these investigations was accomplished using the inert-gas shielded metal-arc (MIG) process. Very limited work on Heat I plate was done using electron beam welding.

The chemical compositions of the three consumable electrode weld-wires that were employed for the MIG welding are tabulated in Table IX. The weldwires were produced by Armetco Inc., using vacuum induction melting procedures; and after drawing, vacuum annealing. The wire procurement specification is presented in Appendix II.

Wire A1 was used exclusively for all welding done under this contract, while wires A2 and A3 were used for the previous Douglas sponsored work. The chemical composition of wire A1 was selected on the basis of preliminary evaluations of weld deposited with wires A2 and A3 and using titanium implant methods (References 5-7).

Welds were deposited in a variety of plate blank sizes. The welds in Heat I plate were made in 9-in. x 10-in. x 3/4-in. and 72-in x 48-in. x 3/4-in blanks. The deposits in Heat B plate were made in either 20-in. x 10-in. x 3/4-in. or 52-in. x 26-in. x 3/4-in. blanks. Figures 1-5 present the specimen blank layout used for the plate blanks. Specimen codings are also shown on the layout, and may be referred to in subsequent sections to identify the locations of weld

TABLE IX

CHEMICAL COMPOSITION OF WELDWIRES

CHEMICAL COMPOSITION, WT. PER CENT

CODE	ARMETCO HEAT NO.	C	Mn	P	S	Si	Cu	Ni	Mo	Al	Ti	Co	B	Zr	N_2	H_2	O_2	SOURCE OF ANALYSIS
A1		0.01	0.04	0.004	0.005	0.04	NA	18.29	4.96	0.10	1.03	9.40	0.003	0.014	0.002	0.0001	0.0015	Armetco
A1	07867	0.01	0.008	0.003	0.005	NIL	NA	17.30 18.7*	5.35*	0.17	0.92*	9.78*	NA	NA	0.001	NA	NA	Douglas
A2	06919	0.02	0.04	0.006	0.009	0.09	NA	17.94	4.75	0.002	0.60	9.74	NA	NA	0.0023	0.0001	0.0016	Armetco
A3	V-192	0.02	0.04	0.003	0.004	0.01	NA	17.95	4.50	0.06	1.20	9.80	NA	NA	0.0033	0.0001	0.0025	Armetco

* Spectrographic Analysis
NA No Analysis

TABLE X - TABULATION OF MECHANICAL TEST SPECIMENS MACHINED FROM HEAT-B WELDED TEST PLATES

PLATES WELDED TOGETHER	MECHANICAL TEST SPECIMENS MACHINED FROM WELDED PLATES
3W1, 3W3	AA-1, AA-2, AA-3, AA-4, AA-5, AA-6
W-22, W-26	BB-1, BB-2, BB-3, BB-4, BB-5, BB-6
W-32, W-34	CC-1, CC-2, CC-3, CC-4, CC-5, CC-6
W-38, W-40	DD-1, DD-2, DD-3, DD-4, DD-5, DD-6
W-5, W-9	GG-1, GG-2, GG-3, GG-4, GG-5, GG-6
W-21, W-25	HH-1, HH-2, HH-3, HH-4, HH-5, HH-6
W-31, W-33	JJ-1, JJ-2, JJ-3, JJ-4, JJ-5, JJ-6
W-42, W-45	KK-1, KK-2, KK-3, KK-4, KK-5, KK-6
4W-39, 4W-49	4A-1 through 4A-12, 4A-31
4W-31, 4W-7	4E-1 through 4E-7, 4E-31
4W-41, 4W-52	4F-1 through 4F-10, 4F-31
4W-42, 4W-54	4G-1 through 4G-7, 4G-31
4W-43, 4W-53	4H-1 through 4H-10, 4H-31
4W-51, 4W-55	4J-1 through 4J-12, 4J-31
2W-3, 2W-1	2A-1 through 2A-12, 2A-31
2W-5, 2W-7	2B-A1 through 2B-A6, 2B-1 through 2B-6, 2B-31
6W-5, 6W-6	6W-1, 6W-2, 6W-3, 6W-4
6W-7, 6W-8	6AW-1, 6AW-2, 6W-5, 6W-6
5W-2, 5W-4	7A-1 through 7A-9, 7A-13, through 7A-25
5W-10, 5W-12	7B-32, 7B-33, 7B-34, 7B-35, 7B-36, 7B-37, 6AW3, 6AW4, 7B-1, 7B-2, 7B-3
5W-6, 5W-8	7C-1 through 7C-6, 7C-32, 7C-33, 7C-34, 7C-35, 7C-36, 7C-37, 7C-10, 7C-11, 7C-12
W-3, W-7	211G-1, 211G-2, 211G-3, 211G-4, 211G-5, 211G-6
W-11, W-19	211H-1, 211H-2, 211H-3, 211H-4, 211H-5, 211H-6
W-1, W-23	211J-1, 211J-2, 211J-3, 211J-4, 211J-5, 211J-6
W-27, W-39	211K-1, 211K-2, 211K-3, 211K-4, 211K-5, 211K-6
W-4, W-8	211A-1, 211A-2, 211A-3, 211A-4, 211A-5, 211A-6
W-12, W-20	211B-1, 211B-2, 211B-3, 211B-4, 211B-5, 211B-6
W-2, W-24	211C-1, 211C-2, 211C-3, 211C-4, 211C-5, 211C-6
W-28	211D-1, 211D-2, 211D-3, 211D-4, 211D-5, 211D-6
2W2, 2W4	212A-1, 212A-2
2W6, 2W8	212B-1, 212B-2
4W8, 4W50	214A-1 through 214A-12
4W9, 4W36	213D-1, 214D-1 through 214D-8
4W10, 4W21	213E-1, 214E-1 through 214E-8
4W11, 4W33	213F-1, 214F-1 through 214F-8
4W12, 4W22	213G-1, 214G-1 through 214G-8
4W23, 4W34	213H-1, 214H-1 through 214H-8
4W24, 4W35	213J-1, 214J-1 through 214J-8
5W9, 5W11	215A-1, 215A-2, 215A-3
5W1, 5W3	215B-1, 215B-2, 215B-3
5W13, 5W15	215C-1, 215C-2, 215C-3
5W5, 5W7	215D-1, 215D-2, 215D-3
8W2, 8W4	222A-1, 222A-2, 222A-3, 222A-4, 222A-5, 222A-6, 222A-7, 222A-8
	222B-1, 222B-2, 222B-3, 222B-4, 222B-5, 222B-6, 222B-7, 222B-8
8W1, 8W3	222C-1, 222C-2, 222C-3, 222C-4, 222C-5, 222C-6, 222C-7, 222C-8
	222D-1, 222D-2, 222D-3, 222D-4, 222D-5, 222D-6, 222D-7, 222D-8

<u>Flat Plate Welding - Specimen Preparation</u> (Cont'd.)

test blanks. Table X designates the sections that were welded

together to provide the welded test specimens for mechanical eval-

uation.

Most of the welds were deposited perpendicular to the plate rolling

direction, although several test welds were also made parallel to

the rolling direction. Welds were deposited primarily in the as-

received mill annealed plate, although a few welds were also deposit-

ed in aged plate.

Prior to welding, the plates were usually grit blasted and always

ground with a portable grinder adjacent to the weld joint prepara-

tion. This procedure served to remove any mill scale that might

otherwise have contaminated the weld deposit. Stainless steel wire

brushing was employed between passes to remove heat tint and excess-

ive weldmetal scale.

The test plates were restrained in the flat position while welding

to prevent lateral distortion. Neither preheat nor postheat was

employed, and the interpass temperature never exceeded 300^OF.

All welds were deposited with standard commercial welding equipment.

Arc current and voltage were continuously recorded for each weld.

The dewpoint of the argon shielding gas was periodically monitored

both at the bottle outlet and welding torch nozzle (employing a

special fitting). The dewpoint was always minus 70^OF or lower.

Figure 42 shows a typical arrangement used for the welding of flat
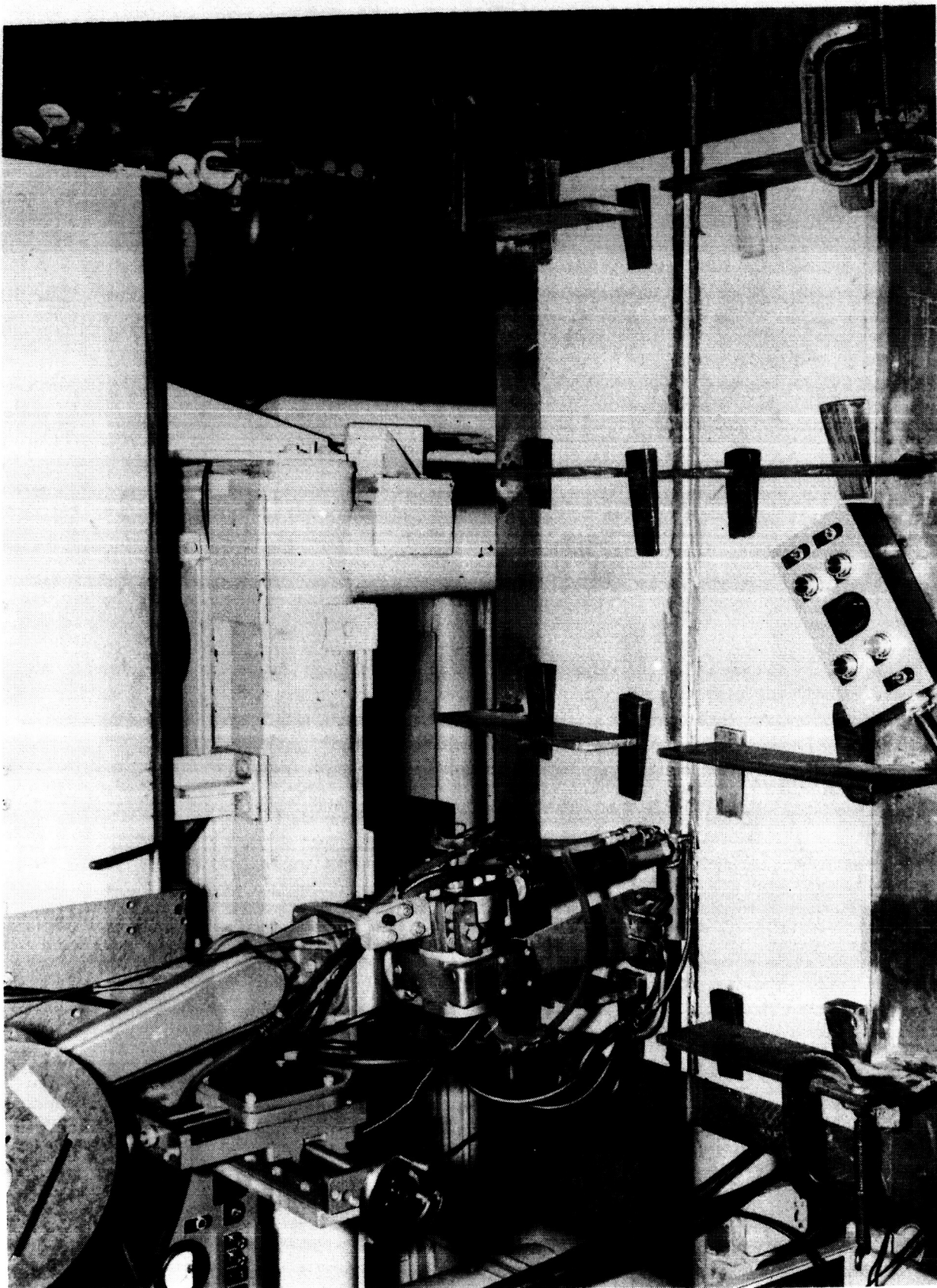
SETUP FOR WELDING FLAT PLATE

FIGURE 42

TABLE XI

WELDING PROCEDURES AND WELDMETAL CHEMICAL COMPOSITIONS

CODE NO.	WELDING PERFORMED BY	BASE PLATE HEAT	WELDING PROCEDURE	APPROX KILO JOULES PER INCH OF WELD PER PASS	WELD WIRE	CHEMICAL COMPOSITION, WT. PERCENT																Notes
						C	Mn	P	S	Si	Cu	Ni	Mo	Al	Ti	Co	B	Zr	N2	H2	O2	
W1	Douglas	I	Two-Pass MIG	120	A2	0.03 0.03	0.03			0.10		17.54 17.40	4.68		0.48 0.45	9.04 9.04			0.03 0.02			
W2	Douglas	I	Two-Pass MIG	120	A2	0.03 0.03	0.04			0.11		17.90 17.90	4.88		1.13 1.09	9.08 8.98			0.02 0.02			Ti IMPLANT USED FOR ALLOYING (SEE REF. 4)
W3	Douglas	I	Two-Pass MIG	130	A3							17.60			1.0	9.35						
W4	Douglas	I	15-Pass MIG	40	A3							NO ANALYSIS PERFORMED										DEPOSIT CHEMISTRY WOULD BE ABOUT THE SAME AS WIRE A3
W5	Douglas	I	6 - Pass MIG	50	A2							NO ANALYSIS PERFORMED										DEPOSIT CHEMISTRY WOULD BE ABOUT THE SAME AS WIRE A2
W6	Douglas	I	1-Pass Electron Beam	20	None							NO ANALYSIS PERFORMED										DEPOSIT CHEMISTRY WOULD BE ABOUT THE SAME AS HEAT-I PLATE
W7	Douglas	B	Two-Pass MIG	105	A1	0.02 0.01						18.75 18.10	4.46 4.45		0.97 0.90	8.9 8.1			0.006 0.006			
W8	Newport News	B	Two-Pass MIG	120	A1	0.015	0.03 0.02	0.005	0.005	0.06	0.04	18.33 18.52	4.74 4.75	0.16	0.75 0.81	8.14 9.15			0.007			
W9	Douglas	B	Two-Pass MIG	155	A1	0.01							4.50 4.75		0.91 0.85	8.05 8.60			0.008			

3.2   <u>Flat Plate Welding - Specimen Preparation</u> (Cont'd.)

plate at Douglas. The Newport News arrangement was similar. Table
XI describes in a general way the different welding procedures that
were employed and designates each weld type by means of a code
number. These weld type codes will be referred to in subsequent
sections. Weld deposit chemical compositions are also presented
and will be discussed in subsequent sections.

Weld types W1 through W6 were evaluated in the previous Douglas
sponsored programs and types W7 through W9 were prepared and eval-
uated in fulfillment of this contract. As may be seen from the
tabulated characteristics in Table XI, the welding procedures in-
cluded principally two-pass MIG deposited welds (about 120,000
joules per inch of weld per pass). However, multipass MIG (about
50,000 joules per inch of weld per pass) and electron beam welds
(about 20,000 joules per inch of weld) are also included.

Figures 43 through 48 present the details of the welding procedures
and joint preparations that were used for each type of weld listed
in Table XI.

3.3   <u>Inspection of Weldments</u>

All weldments were radiographically inspected, and most were also
surface dye penetrant inspected. Radiographic quality was rated
per MIL-R-11468. Welds or weld sections were judged to be accept-
able for testing only if the quality conformed to Class-I Standards.
Dye penetrant was employed to detect surface cracks in weldmetal
and heat-affected regions.

JOINT CONFIGURATION AND WELDING
CONDITIONS FOR TYPES – W1 AND W2 WELDS

W1 JOINT DESIGN

W3 JOINT DESIGN
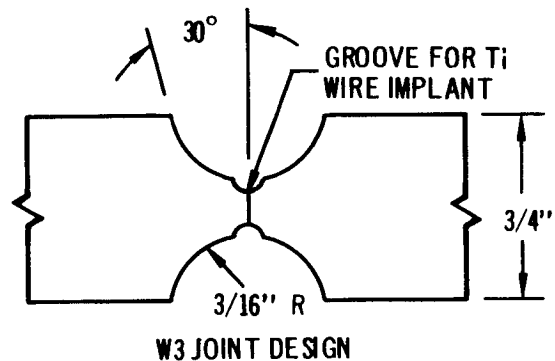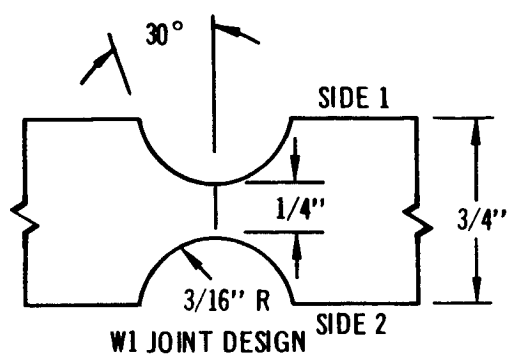
SIDE 1

CURRENT – 475 AMPERES

VOLTAGE – 32 VOLTS

TRAVEL SPEED – 7.5 INCHES PER MIN (ipm)

PROCESS: MIG, DCRP
ELECTRODE: 0.093 – IN. DIAMETER TYPE A2

TORCH GAS: 80 CFH ARGON

TRAIL SHEILD: 190 CFH ARGON

TORCH ANGLE: 3° FOREHAND
POWER SOURCE; CONSTANT POTENTIAL

BASE PLATE: HEAT 1, 3/4 – IN THICK 18 Ni-7Co.-5Mo PLATE

SIDE 2

CURRENT – 475 AMPERES

VOLTAGE – 32 VOLTS

TRAVEL SPEED – 7.5 INCHES PER MIN.

FIGURE 43

JOINT CONFIGURATION AND WELDING
CONDITIONS FOR TYPE – W3 WELDS
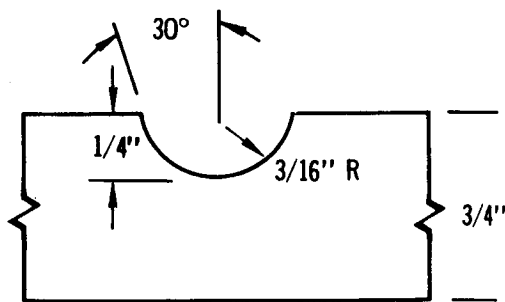
JOINT DESIGN
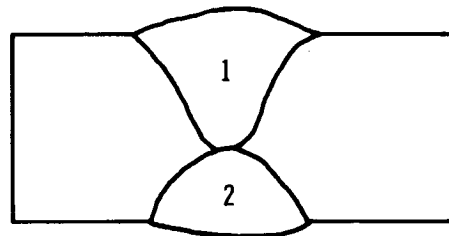
SIDE TWO BEVELED AFTER WELDING
SIDE ONE (SAME GROOVE AS SIDE ONE)

SIDE 1

CURRENT – 540 AMPERES
VOLTAGE – 31 VOLTS
TRAVEL SPEED – 7.5 (ipm)

SIDE 2

CURRENT – 490 AMPERES
VOLTAGE – 33 VOLTS
TRAVEL SPEED – 7.5 (ipm)

PROCESS: MIG DCRP
ELECTROD: 0.093 – IN. DIAMETER TYPE A3
TORCH GAS: 80 CFH ARGON
TRAIL SHEILD: 190 CFH ARGON
TORCH ANGLE: 3° FOREHAND
POWER SOURCE: CONSTANT POTENTIAL

BASE PLATE: HEAT-1, 3/4-IN THICK 18Ni–Co–5Mo PLATE

FIGURE 44

JOINT CONFIGURATION AND WELDING CONDITIONS FOR TYPE- W4 WELDS

JOINT DESIGN

BEVELED AFTER WELDING
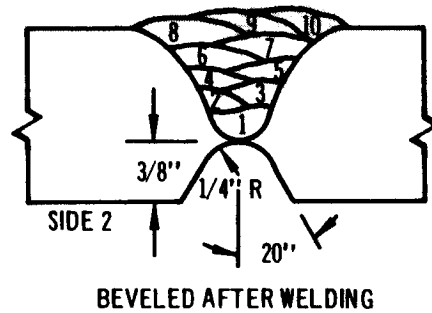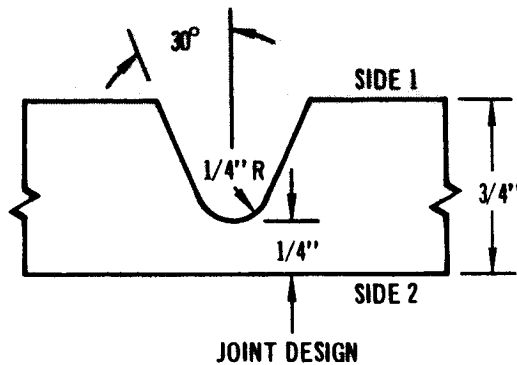
	SIDE 1				SIDE 2		
PASS NO.	CURRENT AMPERES	VOLTS	TRAVEL SPEED i.p.m	PASS NO.	CURRENT AMPERES	VOLTS	TRAVEL SPEED, i.p.m.
1	580	29	18.5	1	420	26.5	18.5
2	510	29	18.5	2	465	26.5	14
3	500	26.5	18.5	3	465	26.5	14
4	450	26.5	18.5	4	465	26.5	14
5	470	26	18.5	5	465	26.5	14
6	450	26.5	18.5				
7	460	26	18.5				
8	455	26	18.5				
9	450	26	18.5				
10	455	26	18.5				

PROCESS: MIG, DCRP

ELECTRODE: 0.093 –IN. DIAMETER TYPE A3

TORCH GAS: 80 CFH ARGON

TRAIL SHEILD: 190 CFH ARGON

TORCH ANGLE: 3° FOREHAND

POWER SOURCE: CONSTANT POTENTIAL

BASE PLATE. HEAT-1, 3/4-IN. THICK 18Ni-7Co-5Mo PLATE

FIGURE 45

JOINT CONFIGURATION AND WELDING
CONDITIONS FOR TYPE – W5 WELDS
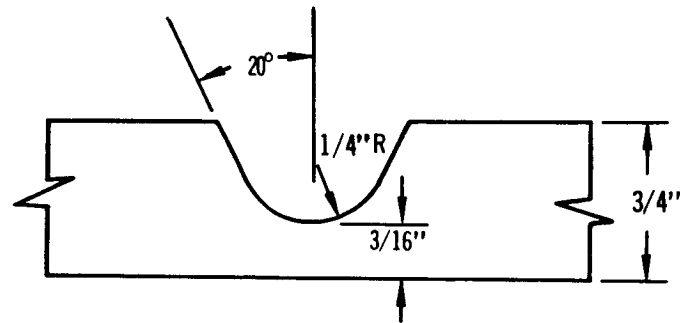
JOINT DESIGN

PASS NO.	CURRENT AMPERES	VOLTS	TRAVEL SPEED i.p.m.
1	350	30	10
2	315	29	12
3	350	29	12
4	350	29	12
5	350	29	12
6	350	29	13
7	350	29	13
8	350	29	13

PROCESS: MIG DCRP
ELECTRODE: 0.062-INCH DIAMETER TYPE A2
TORCH GAS: 60 CFH ARGON
TRAIL SHEILD: 60 CFH ARGON
POWER SOURCE: CONSTANT POTENTIAL
TORCH ANGLE: 3° FOREHAND
BASE PLATE: HEAT-1, 3/4-IN. THICK 18Ni-7CO-5MO PLATE

FIGURE 46

JOINT CONFIGURATION AND WELDING
CONDITIONS FOR TYPE – W6 WELD

.060 GAP

3/4"

BACK UP PLATE
(18Ni-7Co-5Mo)

MELT THROUGH WELD
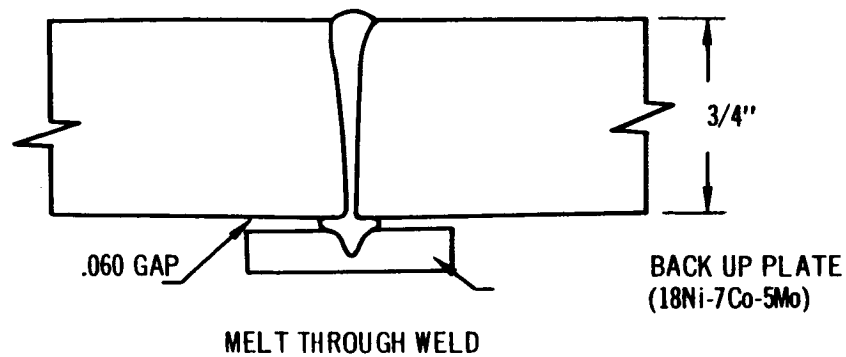
ELECTION BEAM WELD CONDITIONS:

BEAM VOLTAGE   30 Kv
BEAM CURRENT   370 Ma
TRAVEL SPEED   34 ipm
GUN TO WORK DISTANCE 1.5 IN
WELDOR-SCIACKY 150KV, .15ma
BASE PLATE: HEAT-1, 3/4-IN THICK 18Ni-7Co-5Mo PLATE

FIGURE 47

JOINT DESIGN AND WELDING CONDITIONS
FOR TYPES W7, W8, AND W9 WELDS

JOINT DESIGN SIDE 2   WELD BEAD PLACEMENT
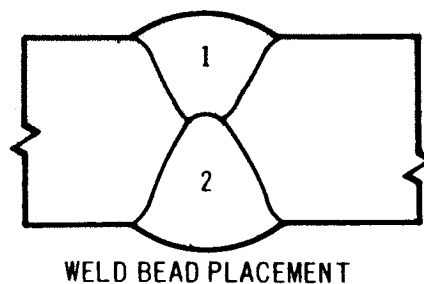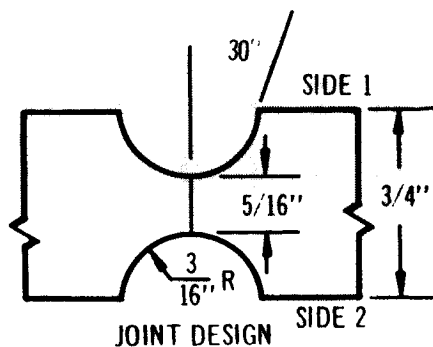
W-7 WELDING CONDITIONS

SIDE 1   SIDE 2

CURRENT	–	425 AMPERES	CURRENT	–	570 AMPERES
VOLTAGE	–	24 VOLTS	VOLTAGE	–	25 VOLTS
TRAVEL SPEED	–	7.5 ipm	TRAVEL SP	–	7.5 ipm

SIDE

W-8 WELDING CONDITIONS

SIDE 1   SIDE 2

CURRENT	–	420 AMPERES	CURRENT	–	460 AMPERES
VOLTAGE	–	32.5 VOLTS	VOLTAGE	–	32.5 VOLTS
TRAVEL SPEED	–	7.5 IPM	TRAVEL SPEED	–	7.5 IPM

W – 9 WELDING CONDITIONS

SIDE 1   SIDE 2

CURRENT	–	485 AMPERES	CURRENT	–	525 AMPERES
VOLTAGE	–	36 VOLTS	VOLTAGE	–	37 VOLTS
TRAVEL SPEED	–	7 ipm	TRAVEL SPEED	–	7 ipm

PROCESS: MIG DCRP
ELECTRODE: 0.093-IN. DIAMETER TYPE A1
TORCH GAS: 70-80 CFH ARGON
TRAIL SHEILD: 90 CFH ARGON (TYPE W7 AND W9), 170 CFH ARGON (TYPE W8)
TORCH ANGLE: 3" FOREHAND
POWER SOURCE: CONSTANT POTENTIAL
BASE PLATE: HEAT-B, 3/4-IN. THICK 18Ni-7Co.-5Mo PLATE

FIGURE 48

3.4   Post-Weld Heat Treatment

Following welding and inspection, the welded plates were machined to provide the required test specimens. These specimens were then aged in accordance with the procedures described for the parent plate.

3.5   Mechanical Testing

Most tensile and fracture toughness testing of weldments was performed in accordance with the procedures described for parent plate. Any exceptions will be described in the appropriate sections. Table X details the locations of welded mechanical test specimens with respect to the individual welded test plate from which the specimens were machined.

Across-the-joint (i.e., transverse to the welding direction) tensile properties were measured using 0.505-in diameter round bars (Figure 6) and by means of 10" x 3/4" x 3/4" square bars (Figure 49). The latter type of specimen was also occasionally employed to determine longitudinal weldment properties. All-weldmetal tensile properties were measured using 0.250-inch diameter round bars (Figure 10). These specimens were carefully machined entirely from the second pass weld for all evaluations presented herein. The longitudinal axis of the 0.250-in diameter specimen was parallel to the longitudinal axis of the weld. Figure 50 illustrates the location of the specimen in the weld.

Fracture toughness evaluations were performed using the 8-in, 24-in.,

10" X ¾" X ¾" TENSILE SPECIMEN

DIA. = 1.000"

$W = .750'' \begin{array}{c} +0.002 \\ -0.001 \end{array}$

1 1/8" R

.375"

2¼"

1 1/8"

10"

3"

1½"

1¾"

2¾"

1¾"
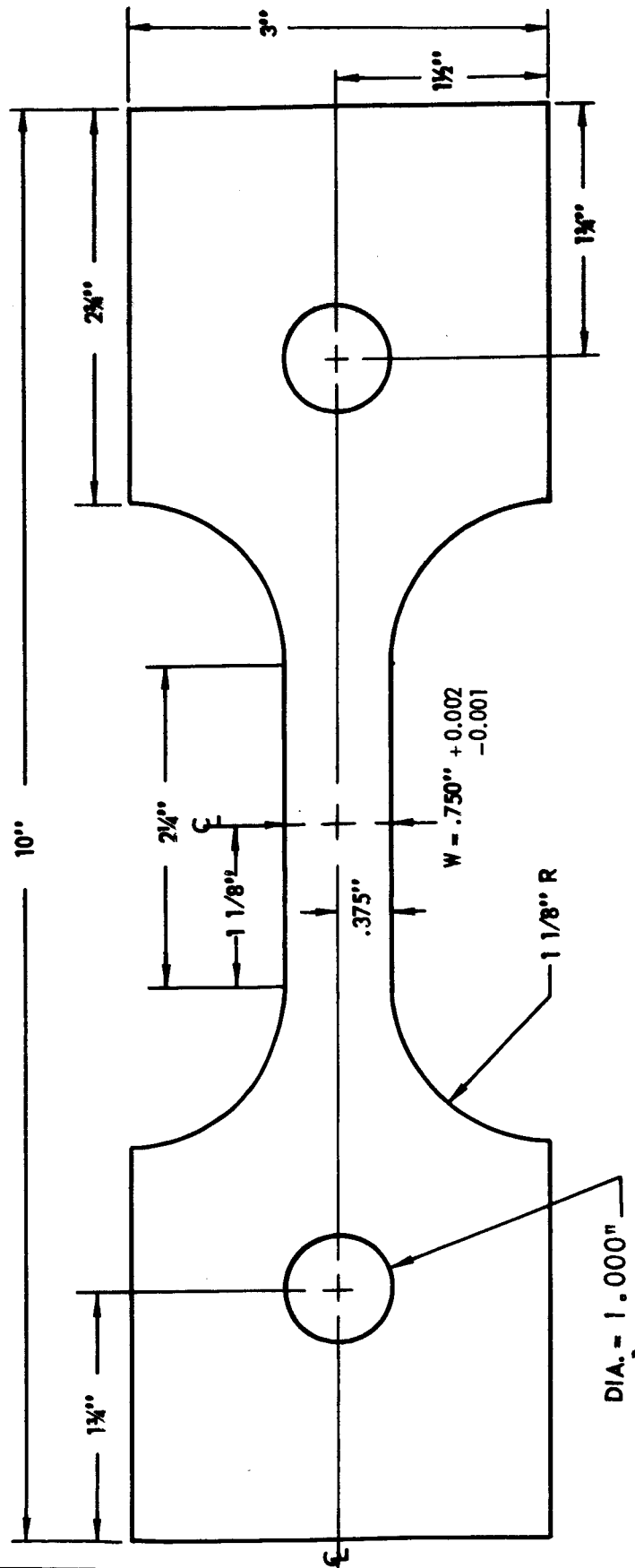
NOTE
WHEN USED IN WELD EVALUATION,
WELDS WILL BE GROUND FLUSH
WITH PLATE SURFACE.

FIGURE 49

TRANSVERSE CROSS-SECTION ILLUSTRATING
THE LOCATION OF THE 0.250-INCH DIAMETER
ALL-WELDMETAL TENSILE SPECIMEN

SECOND WELD PASS

3/8" FINAL MAJOR DIAMETER
(THREADED END) OF LONGITUDINAL
ALL-WELDMETAL 0.250" TENSILE
SPECIMEN.

FIRST WELD PASS
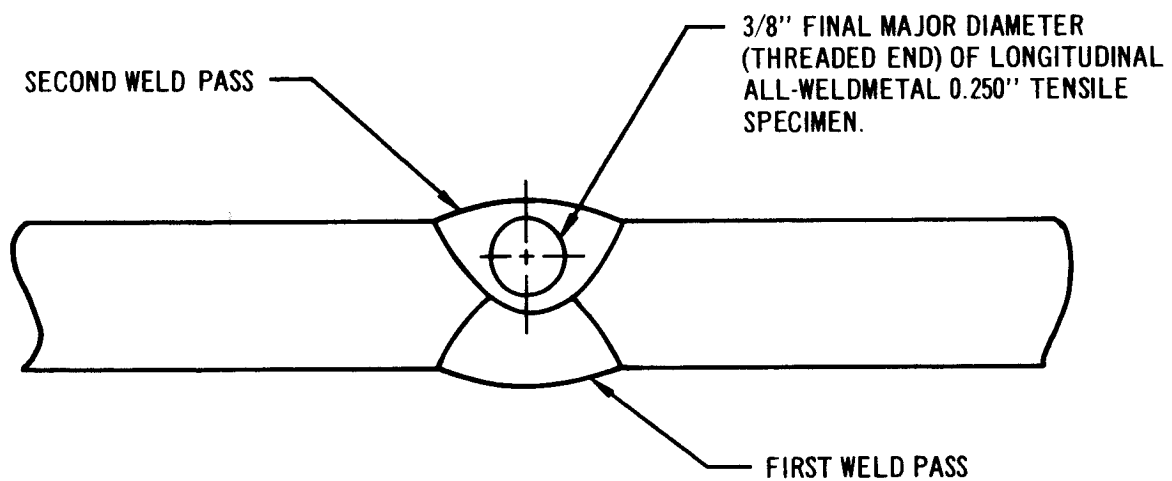
TRANSVERSE CROSS SECTION

FIGURE 50

3.5   Mechanical Testing (Cont'd.)

and 48-in PTC specimen types illustrated previously in Figures 7,8,
9 and 33. Several different specimen orientations with respect to
the welding and plate rolling directions were investigated for weld-
metal and heat-affected zone regions. Details of the various
orientations will be described in the appropriate forthcoming
sections.

3.6   Weldment Soundness

Some unexpected difficulty was encountered initially in producing
welds of the required quality. An unusually high incidence of
porosity developed in the first test welds made using the W9 con-
ditions (See Tables XI and Figure 48). The incidence of porosity
was sporadic and efforts to establish the cause or causes were not
successful. Since a systematic study of porosity formation was not
an objective of this contract, empiricaly guided modifications in
the welding procedure were employed to eliminate the problem. The
W7 and W8 conditions were capable of producing sound welds comply-
ing with the specified requirements.

The reasons for the improvement in weld quality produced by the
change in welding conditions are not fully explainable. Work on
the mechanisms of porosity formation in maraging alloys is worthy
of further study.

Radiographic and dye-penetrant inspections failed to reveal signif-
icant weldmetal or heat-affected zone cracking in any of the welds.

3.6   Weldment Soundness (Cont'd.)

However, occasional crater cracking produced by inadequate crater
fill was observed. Such cracking may be controlled by the automated
adjustment of welding conditions upon termination of a weld. Micro-
scopic examination of several weld sections failed to reveal any
subsurface crack-like defects.

3.7   Effects of Welding and Heat Treatment Variables on Aging Response

This section presents data pertaining to the effects of post-weld
aging treatments on the tensile and hardness properties of welds.
The behavior of several weld types are described and compared.
Both all-weldmetal and across-the-joint properties are discussed.

3.7.1   Effects of Aging Heat Treatment on the Aging Response of Type W9 Weldmetal

Although, as previously discussed, Type W9 welds were often charac-
terized by unacceptable porosity, it was possible to machine
specimens from porosity-free regions. All-weldmetal 0.250-in
diameter specimens were machined from welds made both in as-received
and in aged plate. The tensile specimens were aged at 875, 900,
and 950°F for times ranging from 1 1/2 to 12 hours. Tensile
property data are tabulated in Table XII and Appendix VII. The
remarks column describes significant features of the fracture
surface (as observed visually) in terms of a letter code. This
letter code is defined in Table XIII and will be referred to
frequently throughout the remainder of this report. The data are
presented graphically in Figures 51, 52 and 53. The data are not

distinguished in terms of prior plate condition since this factor
did not affect the results. The dependence of tensile strength
properties on aging time at 875 and 900°F are quite similar. Both
ultimate and yield strength tend to increase with increasing time.
However, peak strength appears to be achieved after six hours at
900°F, while no peaking is evident at 875°F. Ductility appears to
decrease drastically with increasing aging time at 875°F. Aging for
6 or 12 hours resulted in virtually nil ductility. The same trend
is apparent for the 900°F specimens. However, scatter in the results
makes the trend much less decisive. The low ductility upon prolonged
aging is also manifested by the coincidence of yield and ultimate
for one specimen aged for 6 hours at 900°F and another aged for 12
hours that failed at relatively low strength without measurable 0.2%
yield.

The tensile strength of specimens aged at 950°F appears to be
virtually independent of aging time. Ductility is uniformly low,
although strengths equivalent to that achieved only after six hours
aging at 875° and 900°F are attained after only 1 1/2 hours at
950°F.

Table XII describes a majority of the type W9 weldmetal specimens
as being characterized by columnar appearing fracture surfaces.
Figure 54 illustrates this typical columnar appearance. This
structure resembles that resulting from fracture along the grain
boundaries of large columnar grains produced in a very slowly

TABLE XII - LONGITUDINAL ALL WELDMETAL TENSILE DATA, SUMMARY

TYPE W9 WELDS IN HEAT-B PLATE

SPEC. NO.	CONDITION OF PLATE PRIOR TO WELDING	ORIENTA- TION	AGING TEMP., (°F)	AGING TIME (HRS)	0.2% YIELD STRENGTH (KSI)	ULTIMATE STRENGTH (KSI)	% ELONG (1" GAGE)	% REDUC- TION IN AREA	REMARKS
21AA1	As Rec'd.	L-AWM	875	1.5	223.5	240.6	8.0	22.3	H
21BB1	As Rec'd.	L-AWM	875	3.0	231.0	247.3	6.0	16.8	H
21CC1	As Rec'd.	L-AWM	875	6.0	250.7	256.3	1.0	2.5	G
21DD1	As Rec'd.	L-AWM	875	12.0	255.1	268.0	1.0	4.1	G
21GG1	Aged	L-AWM	875	1.5	217.6	234.5	8.5	29.6	H
21HH1	Aged	L-AWM	875	3.0	224.4	239.7	6.0	22.8	H
21JJ1	Aged	L-AWM	875	6.0	254.5	263.3	1.0	3.1	G
21KK1	Aged	L-AWM	875	12.0	260.8	276.2	2.0	3.2	G
21AA3	As Rec'd.	L-AWM	900	1.5	232.4	247.7	1.0	5.5	G, H
21BB3	As Rec'd.	L-AWM	900	3.0	240.8	258.7	4.5	18.3	G,H
21CC3	As Rec'd.	L-AWM	900	6.0	257.4	257.4	1.0	6.3	G
21DD3	As Rec'd.	L-AWM	900	12.0	NA	249.3	BOGM	1.6	H
21GG3	Aged	L-AWM	900	1.5	225.7	241.1	6.0	24.6	H
21HH3	Aged	L-AWM	900	3.0	240.1	249.3	1.0	1.6	G
21JJ3	Aged	L-AWM	900	6.0	261.7	274.1	3.0	6.3	G
21KK3	Aged	L-AWM	900	12.0	261.8	275.6	1.0	3.3	G
21AA5	As Rec'd.	L-AWM	950	1.5	268.7	274.7	4.0	6.3	G
21BB5	As Rec'd.	L-AWM	950	3.0	268.1	282.4	2.0	9.7	G
21CC5	As Rec'd.	L-AWM	950	6.0	NA	265.6	1.0	3.1	G
21DD5	As Rec'd.	L-AWM	950	12.0	265.3	276.0	1.0	0.8	G
21GG5	Aged	L-AWM	950	1.5	253.9	268.6	4.0	14.1	H
21HH5	Aged	L-AWM	950	3.0	262.2	273.5	1.0	2.3	G
21JJ5	Aged	L-AWM	950	6.0	254.6	273.5	3.0	10.9	G
21KK5	Aged	L-AWM	950	12.0	266.5	269.8	1.0	3.3	G

NOTES:
1. L-AWM - Longitudinal all weldmetal specimen; 0.250-in. diam.
2. See Table XIII for definition of Remark codes.
3. BOGM - Broke outside gage marks
4. NA - not available
5. Plates aged prior to welding were aged at 900°F for 3 hours.

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TABLE XIII

CODE DEFINITIONS FOR VARIOUS TYPES OF OBSERVED FAILURES

Code	Special Features of Failure
A	Failure through weldmetal
B	Failure through heat-affected zone eyebrow
C	Failure through heat-affected zone between eyebrow and fusion line
D	Mixed failure - weldmetal and heat-affected zone
E	Failure through weldmetal - porosity on fracture surface (See Fig. 89)
F	Lack of fusion evident on fracture surface (See Fig. 88)
G	Columnar structure predominant on fracture surface (See Fig. 54)
H	Cup and cone fracture
J	Gold flakes on fracture surface - possible fracture initiation sites
K	Possible prior defect on fracture surface

EFFECT OF AGING TIME AT 875°F ON TYPE W9
ALL WELDMETAL UNIAXIAL TENSILE PROPERTIES
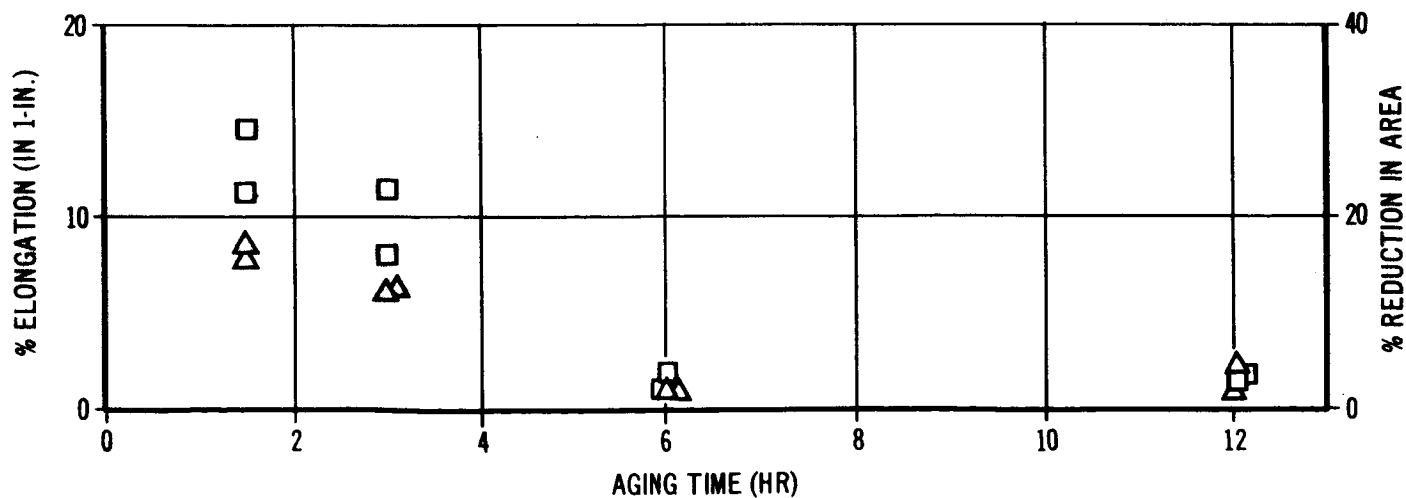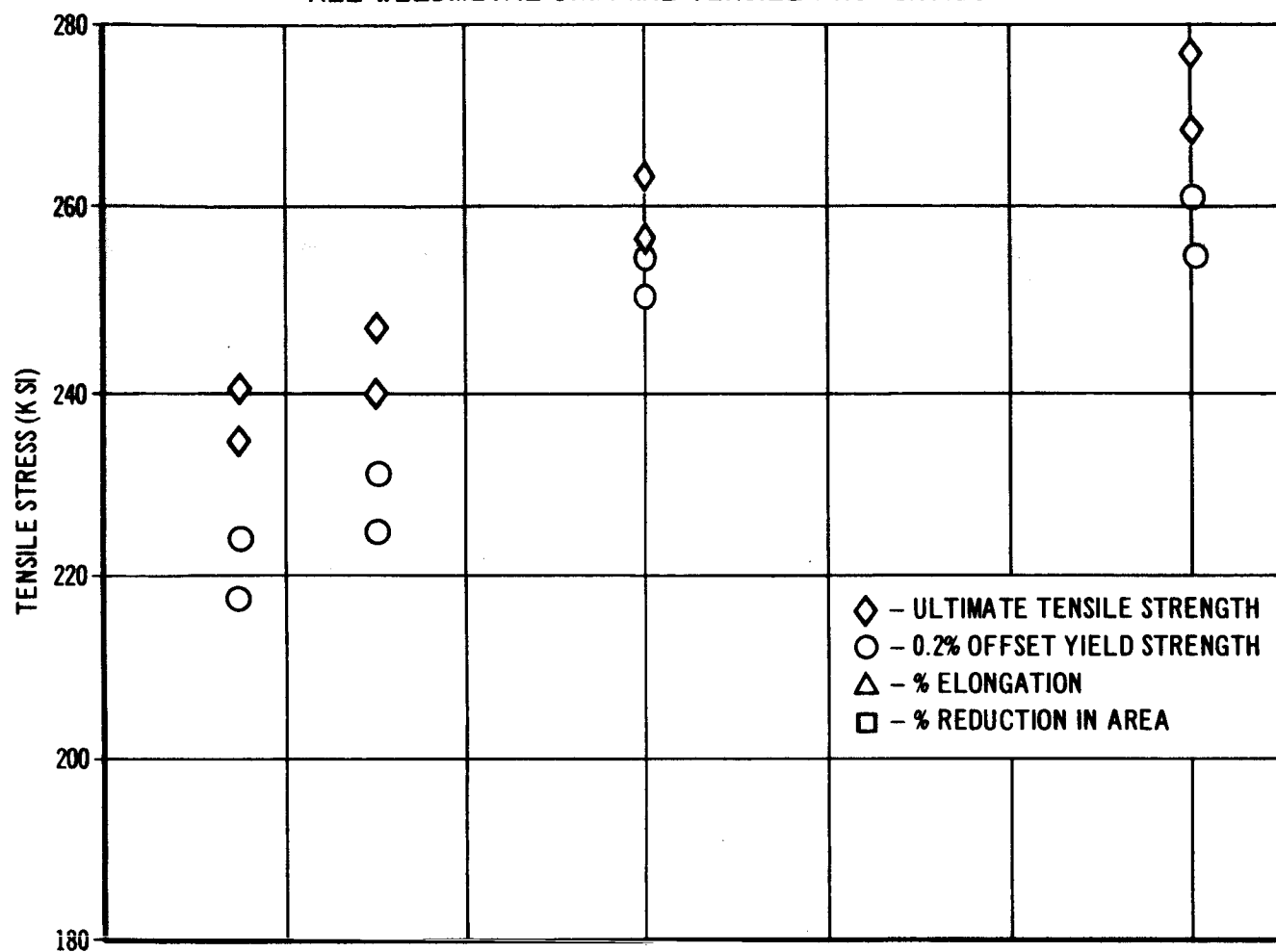
FIGURE 51

EFFECT OF AGING TIME AT 900°F ON TYPE W9
ALL WELDMETAL UNIAXIAL TENSILE PROPERTIES

◇ – ULTIMATE TENSILE STRENGTH
○ – 0.2% OFFSET YIELD STRENGTH
△ – % ELONGATION
□ – % REDUCTION IN AREA

FIGURE 52

98
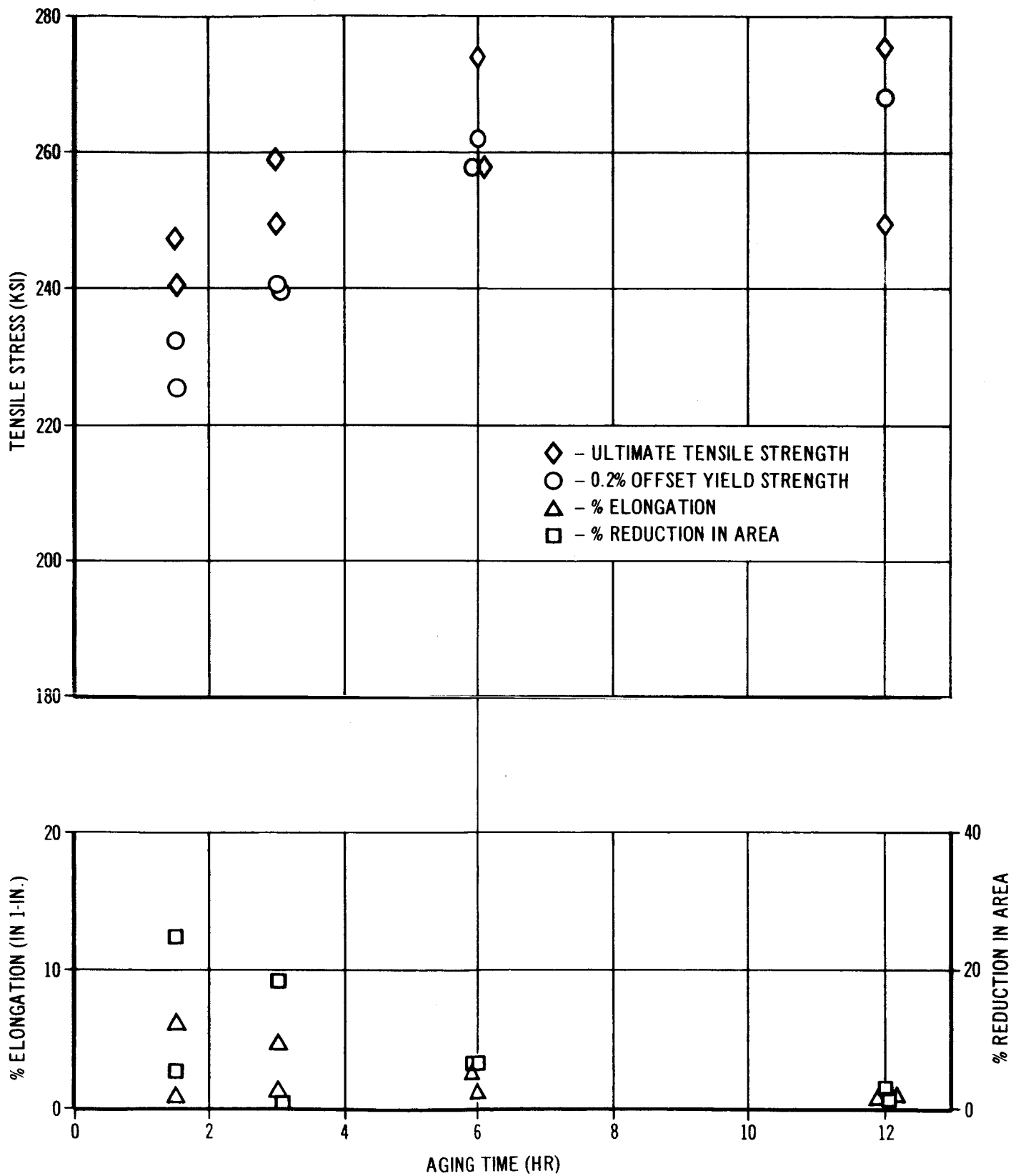
EFFECT OF AGING TIME AT 950°F ON TYPE W9
ALL WELDMETAL UNIAXIAL TENSILE PROPERTIES

◇ – ULTIMATE TENSILE STRENGTH
○ – 0.2% OFFSET YIELD STRENGTH
△ – % ELONGATION
□ – % REDUCTION IN AREA
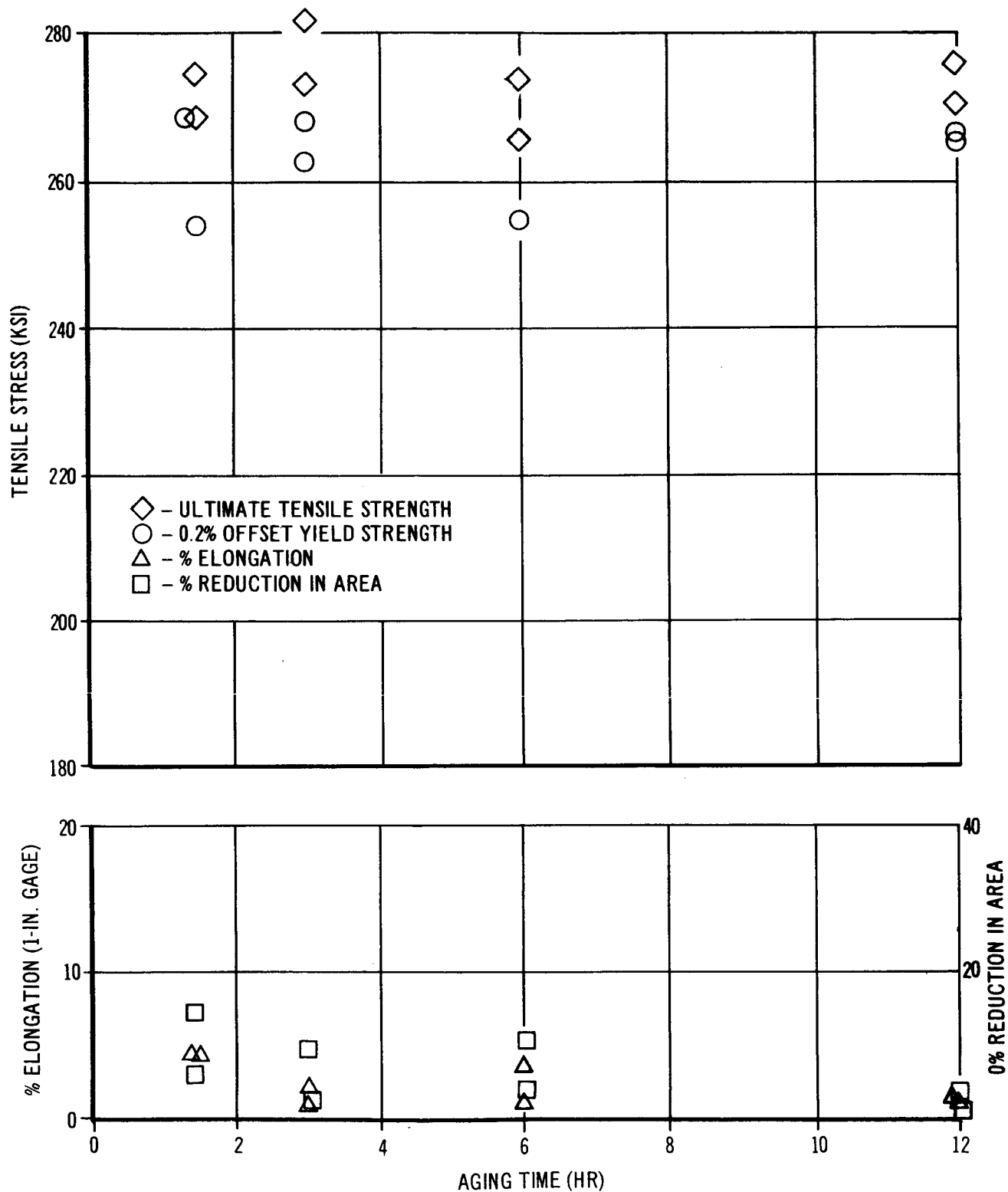
FIGURE 53

<u>Effects of Aging Heat Treatment on the Aging Response of Type W9 Weldmetal</u> (Cont'd.)

solidifying weld deposit. The type W9 welds were deposited using the highest unit energy investigated (approximately 150 Kilo Joules per inch of weld per pass), and would be expected to possess the coarsest grain structure. Electron fractographic examinations, described in a subsequent section indicate that the columnar fracture surfaces were laden with what is believed to be a damaging phase. This phase, identified as TiN, could substantially degrade ductility. It is not known whether the high concentration of TiN resulted from the high welding energy input or other unknown factors. The data do indicate, however, that the effects of welding energy input, and its attendent affect on weldmetal microstructure and properties, deserves further investigation.

3.7.2   <u>Effects of Aging Heat Treatment on the Aging Response of Types W7 and W8 Weldmetal</u>

Figures 55, 56 and 57 depict the dependence of types W7 and W8 all-weldmetal tensile properties on post weld aging heat treatment. Appendix VIII summarizes the same data. Figure 58 presents hardening response data for Type W8 weldmetal.

Examination of Figures 55-57 reveals that strength is significantly affected by aging time and temperature (Type W7 and W8 weldmetal respond similarly). Aging at 875 and 900°F produces continuously increasing strength up to 12 hours. Aging at 950°F produces peak strength at about 6 hours and a slight decrease after 12 hours. The weldmetal strength ranges from about 85 to approximately 100

TYPICAL COLUMNAR FEATURES ON TYPE W9
ALL WELDMETAL TENSILE SPECIMEN FRACTURE SURFACE

FIGURE 54

<u>Effects of Aging Heat Treatment, on the Aging Response of Types W7 and W8 Weldmetal</u> (Cont'd.)

per cent of that possessed by the Heat-B parent plate (compare Figures 55-57 to Figures 21-22). Aging at $950^\circ F$ produced virtually equivalent strength in the weldmetal and parent plate for the full range of aging times investigated. Hardening response (Figure 58) parallels the strengthening response behavior. Ductility (as measured by both per cent elongation and per cent reduction in area) is relatively unaffected by aging treatment, although it appears to decrease slightly as aging time increases. Ductility values are generally slightly lower than for plate.

Unlike the W9 welds, columnar fracture surfaces were not observed on W7 and W8 all weldmetal tensile fracture surfaces. Both W7 and W8 type welds were deposited at significantly lower specific energy inputs than type W9. Thus it appears that the welding energy input may be an important factor influencing mechanical properties. However, as will be discussed later, welding energy input is probably significant only insofar as it may influence the dispersion of TiN in weldmetal.

3.7.3 <u>Effects of Welding Procedure and Aging Heat Treatment on the Aging Response of Heat-Affected Regions</u>

The aging response of heat-affected zones has been investigated by means of hardening response measurements and across-the-joint tensile properties. The data presented in this section indicate that although some strength impairment does prevail in heat-affected regions, the problem does not appear to be a major one.

EFFECT OF AGING TIME AT 875°F ON ALL-WELDMETAL
UNIAXIAL TENSILE PROPERTIES OF DEPOSITS IN HEAT-B PLATE
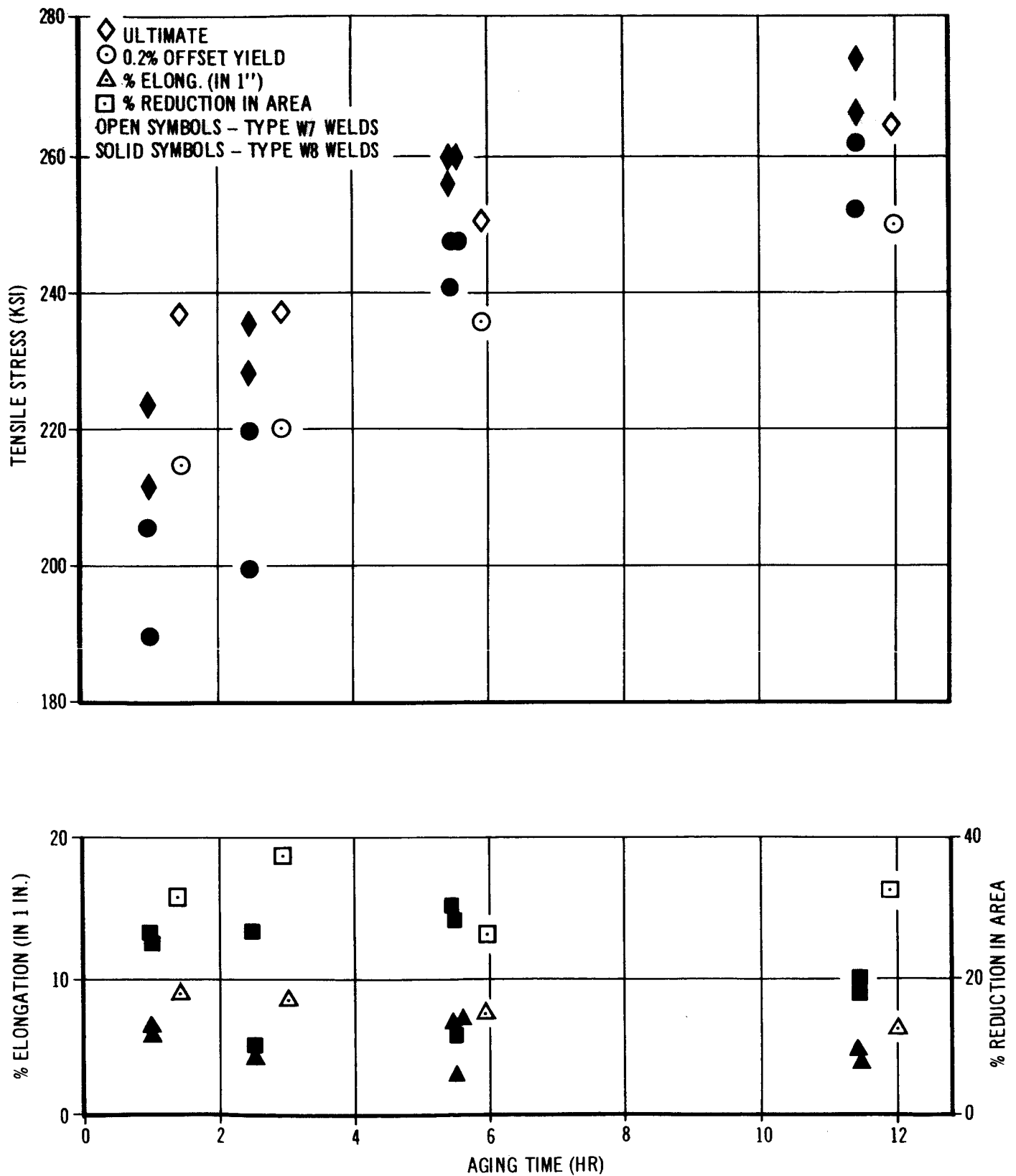
FIGURE 55

EFFECT OF AGING TIME AT 900°F ON ALL-WELDMETAL
UNIAXIAL TENSILE PROPERTIES OF DEPOSITS IN HEAT-B PLATE

◇ ULTIMATE
⊙ 0.2% OFFSET YIELD
△ % ELONG. (IN 1")
□ % REDUCTION IN AREA
OPEN SYMBOLS — TYPE W7 WELDS
SOLID SYMBOLS — TYPE W8 WELDS
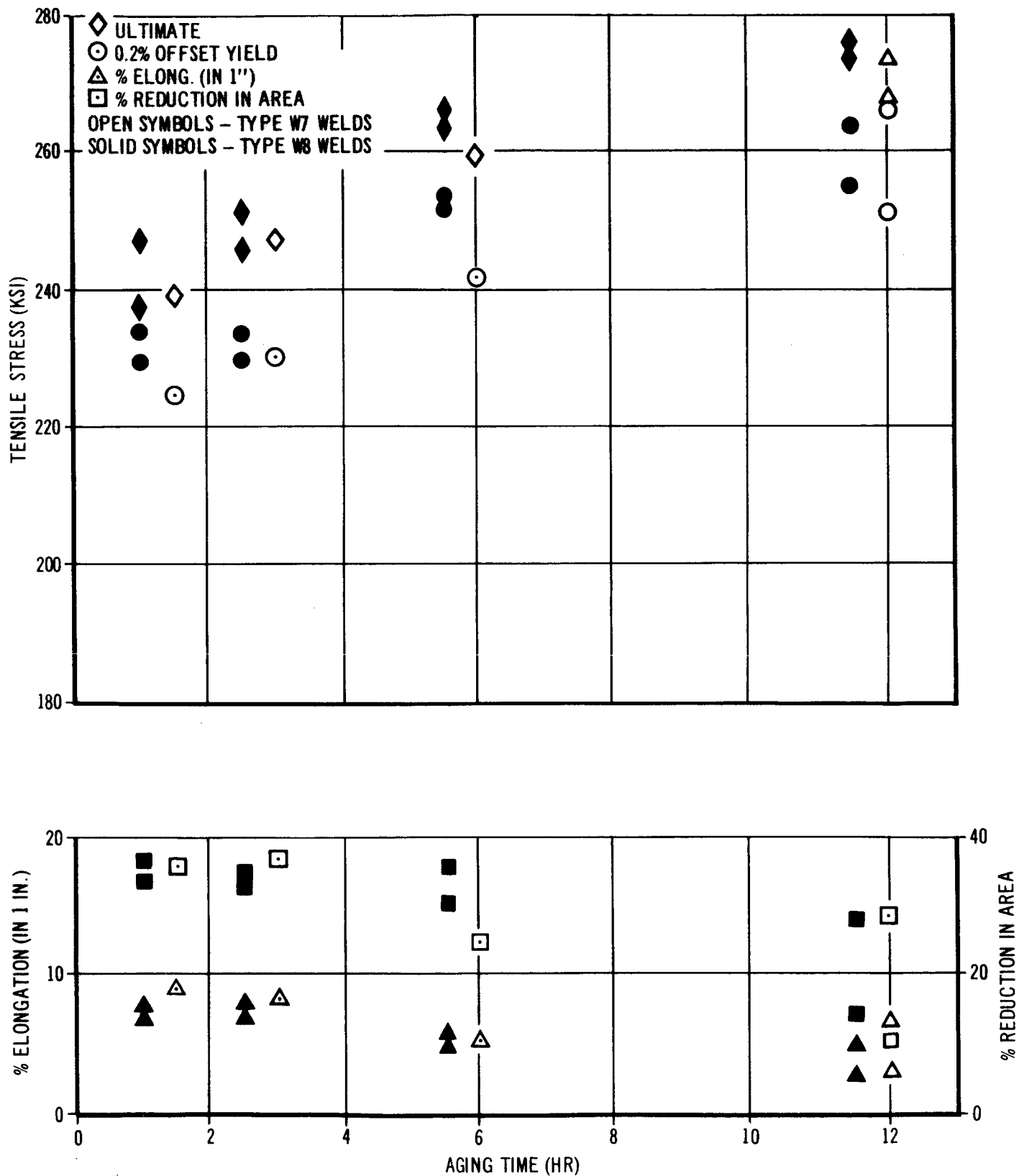
FIGURE 56

EFFECT OF AGING TIME AT 950°F ON ALL-WELDMETAL
UNIAXIAL TENSILE PROPERTIES OF DEPOSITS IN HEAT-B PLATE
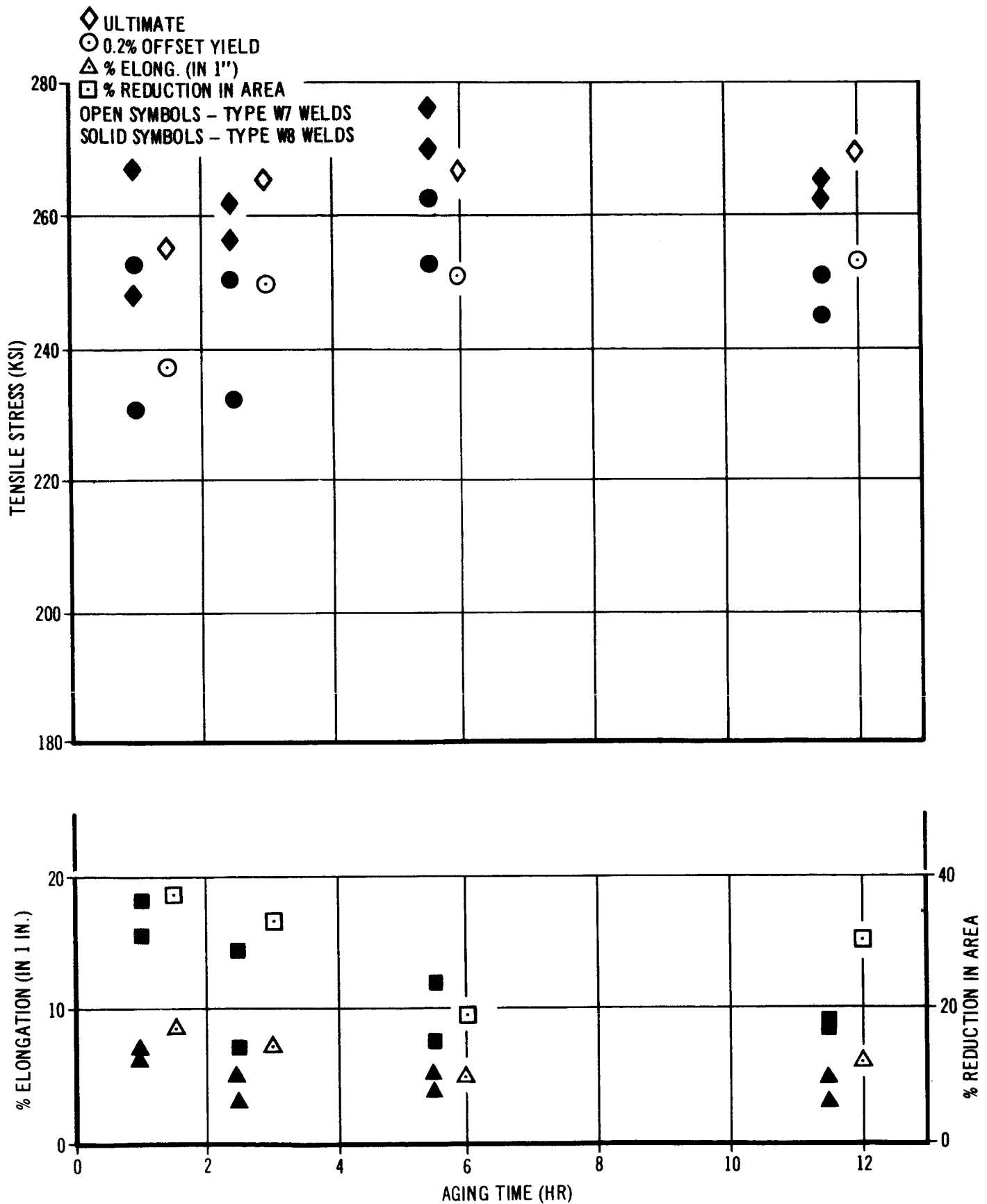
FIGURE 57

EFFECT OF AGING TIME AND TEMPERATURE ON
WELDMETAL HARDNESS
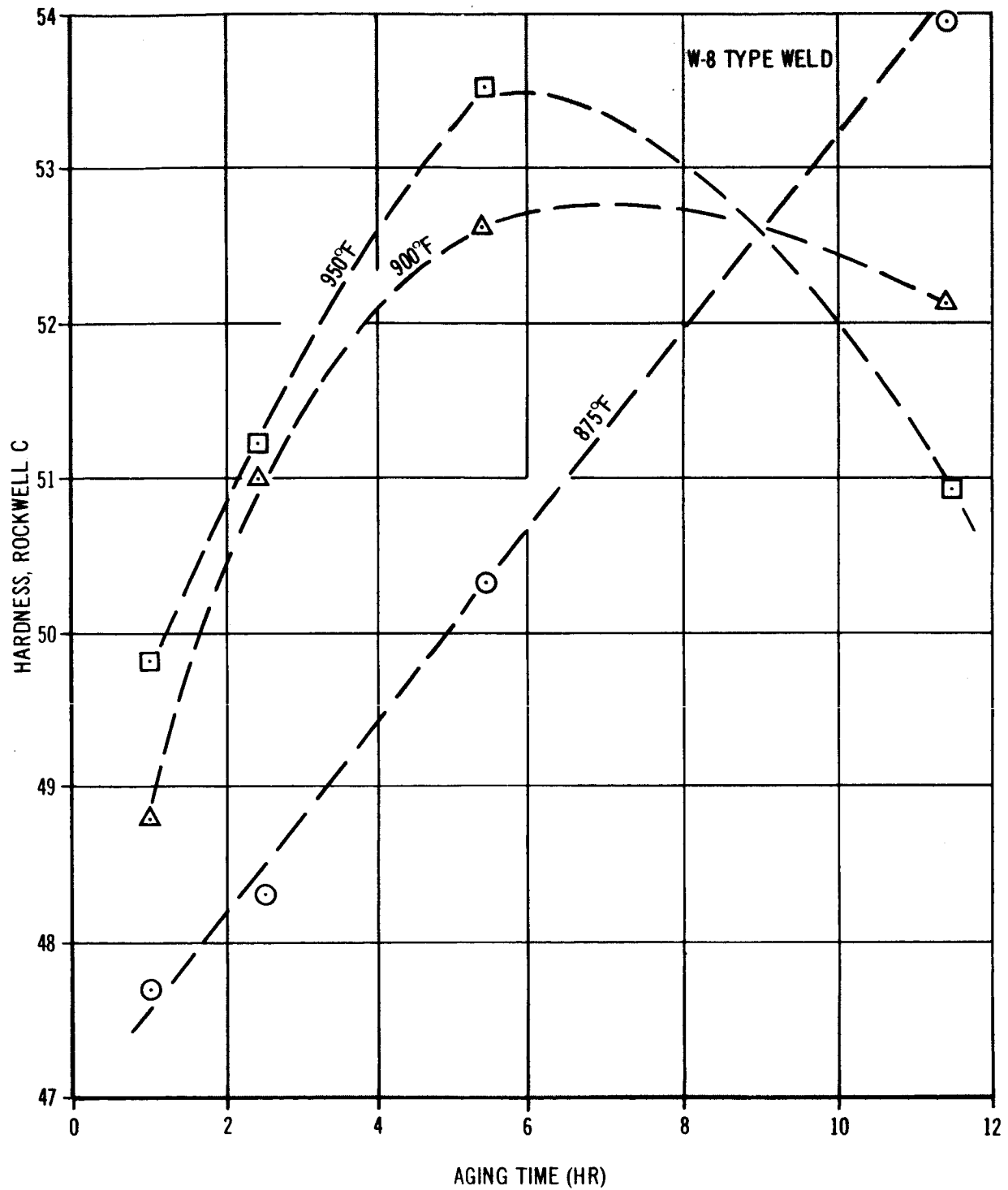
FIGURE 58

3.7.3   <u>Effects of Welding Procedure and Aging Heat Treatment On the Aging</u>
         <u>Response of Heat-Affected Regions</u> (Cont'd.)

Previous work (References 5-7) demonstrated that heat affected zone
softening is produced in regions where brief exposures between
about 1,200 and 1300°F occur. This softening has been shown to
result from partial reversion and stabilization of austenite which
does not respond fully to subsequent aging treatments, (References
8-11). Figure 59 illustrates the softening which occurs in the
heat-affected zone as a result of austenite reversion.

Figure 60 depicts the effect of specific welding energy input on the
minimum heat-affected zone strength of several types of welds
previously described. Specific welding energy (i.e., energy per
inch of weld per weld pass) was selected arbitrarily, and total
integrated energy input could also be used. In either case the con-
clusions presented below would be the same. Tensile specimens
(0.505-inch round bars) were machined transverse to the welding
direction (the welding direction paralleled the rolling) and aged
for 12 hours at 900°F. Under these conditions all failures occurred
through heat-affected zones. Figure 61 illustrates a typical failure
location for the two-pass welds. Fracture occurs substantially
through the "eyebrow" regions as illustrated in the figure (where
partial austenite reversion has occurred). It is noteworthy that
the failure generally did not propagate through the coarsest-
grained regions of the heat-affected zone adjacent to the fusion
line. The strength data presented in Figure 60 may thus be inter-
preted to represent the minimum heat-affected zone ultimate tensile

<u>Effects of Welding Procedure and Aging Heat Treatment On the Aging</u>
        <u>Response of Heat-Affected Regions</u> (Cont'd.)

        strength for the given welding procedures and the single postweld

        aging treatment.

        The data presented in Figure 60 demonstrate that up to about 10

        per cent loss in strength may occur in heat-affected regions. No

        decisive dependence on the specific welding energy input (joules

        per inch of weld per pass) may be ascertained from the data. Thus,

        it appears that over a wide range of welding thermal conditions, the

        heat-affected zone behavior remains relatively constant.

        Figures 62 through 65 present additional data on the aging response

        of heat-affected zones in weldments of Type W2, W7, W8 and W9.

        Tabulated data are presented in Appendices VII and VIII. The data

        represent properties of across-the-joint specimens (0.505-inch

        diameter round bars) the majority of which failed through the

        "eyebrow" regions. Some W9 types failed through weldmetal exhibit-

        ing the columnar appearance previously described. Welds made in as-

        received as well as aged plate (900°F, 3 hours) are presented in

        Figures 63-65 for type W7 and W8 welds. Welds made in as-received

        or aged plate are not differentiated in the figures to simplify the

        presentation. However, welds deposited in aged plate generally

        exhibited slightly higher strengths after aging than those deposited

        in as-received plate. Apparently, previously aged plate is not

        impaired quite as much as as-received plate by the thermal effects

        of welding. Perhaps less austenite reversion occurs in the eyebrow

        regions of previously aged plate. The presence of a precipitate,

containing austenite stabilizing elements, could also retard the rate of austenite reversion since additional time would be required for precipitate solution and subsequent reversion.

As may be seen from the tabulation in Appendices VII and VIII some of the tensile failures propagated through heat-affected zones away from the eyebrow. Thus it appears that some strength degredation may occur in other heat-affected zone regions as well. The tensile strength data, nonetheless, may be regarded as being a measure of the minimum heat-affected zone strength values. Reduction in area data give an indication of the relatively ductile nature of this region. Somewhat suprisingly, the data indicate that type W8 welds did not strengthen upon aging as well as the type W7. Additional across-the-joint and longitudinal specimens from type W7 and W8 welds were tested employing 10" x 3/4" x 3/4" specimens (Figure 49). Table XIV presents the tensile results after the specimens were aged for 3 hours at $900^{\circ}F$. The data indicate, as before, that the aging response of the type W7 welds was somewhat superior to that of type W8 welds. No satisfactory explanation can be offered to explain this difference. It is very unlikely that the small difference in specific energy input could account for the variation.

The data presented in Figures 62 through 65 also show that the impaired heat-affected zone regions may be strengthened by prolonged aging at the lower aging temperatures (875 and $900^{\circ}F$). The strength after prolonged aging approaches approximately 95% of the parent-

HARDENING RESPONSE IMPAIRMENT IN PLATE HEAT-AFFECTED ZONE
TYPE W2 WELDS-HEAT-1 PLATE

FIGURE 59

110
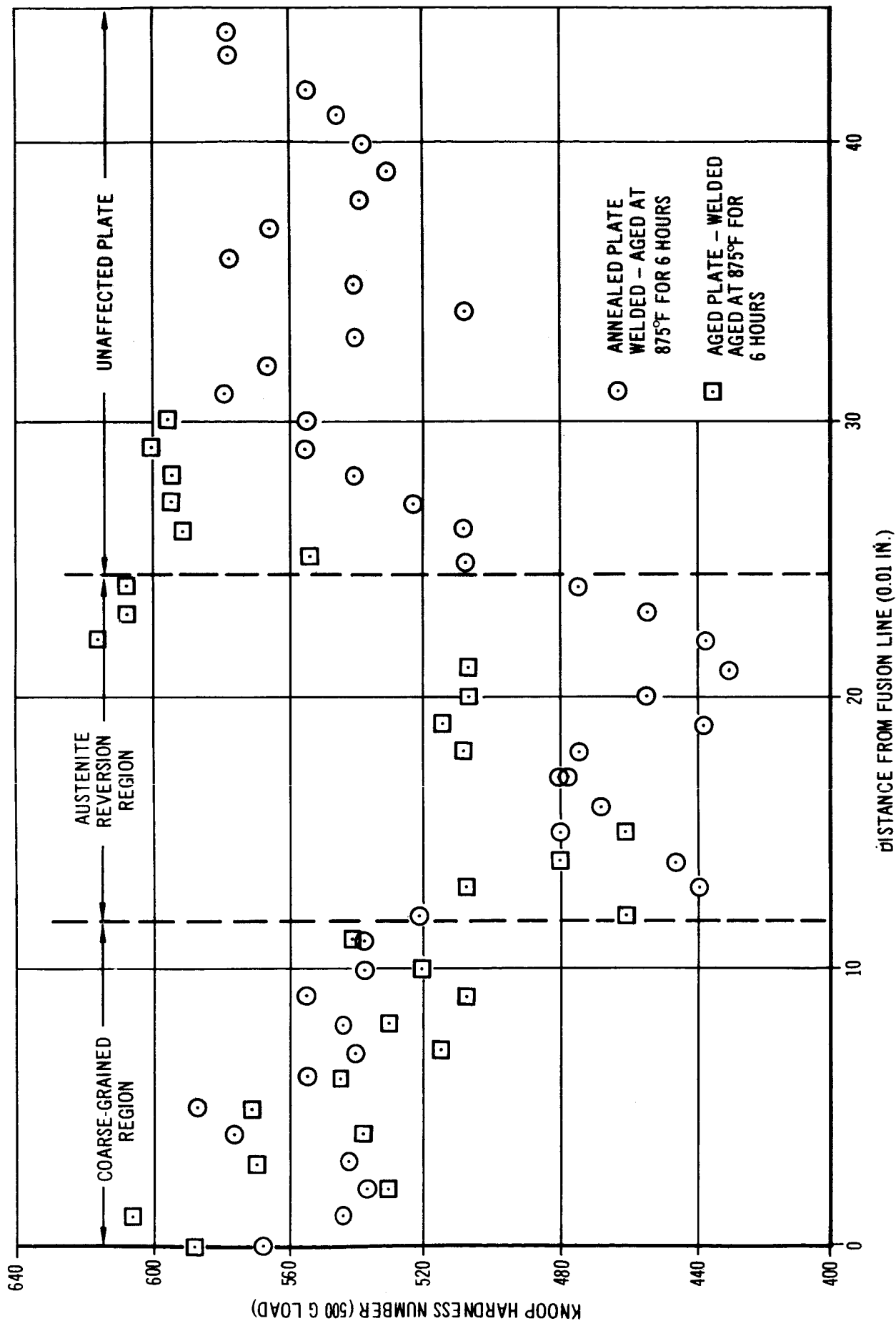
EFFECT OF WELDING ENERGY INPUT ON MINIMUM
HEAT-AFFECTED ZONE TENSILE STRENGTH AFTER 900F, 12 HR AGING
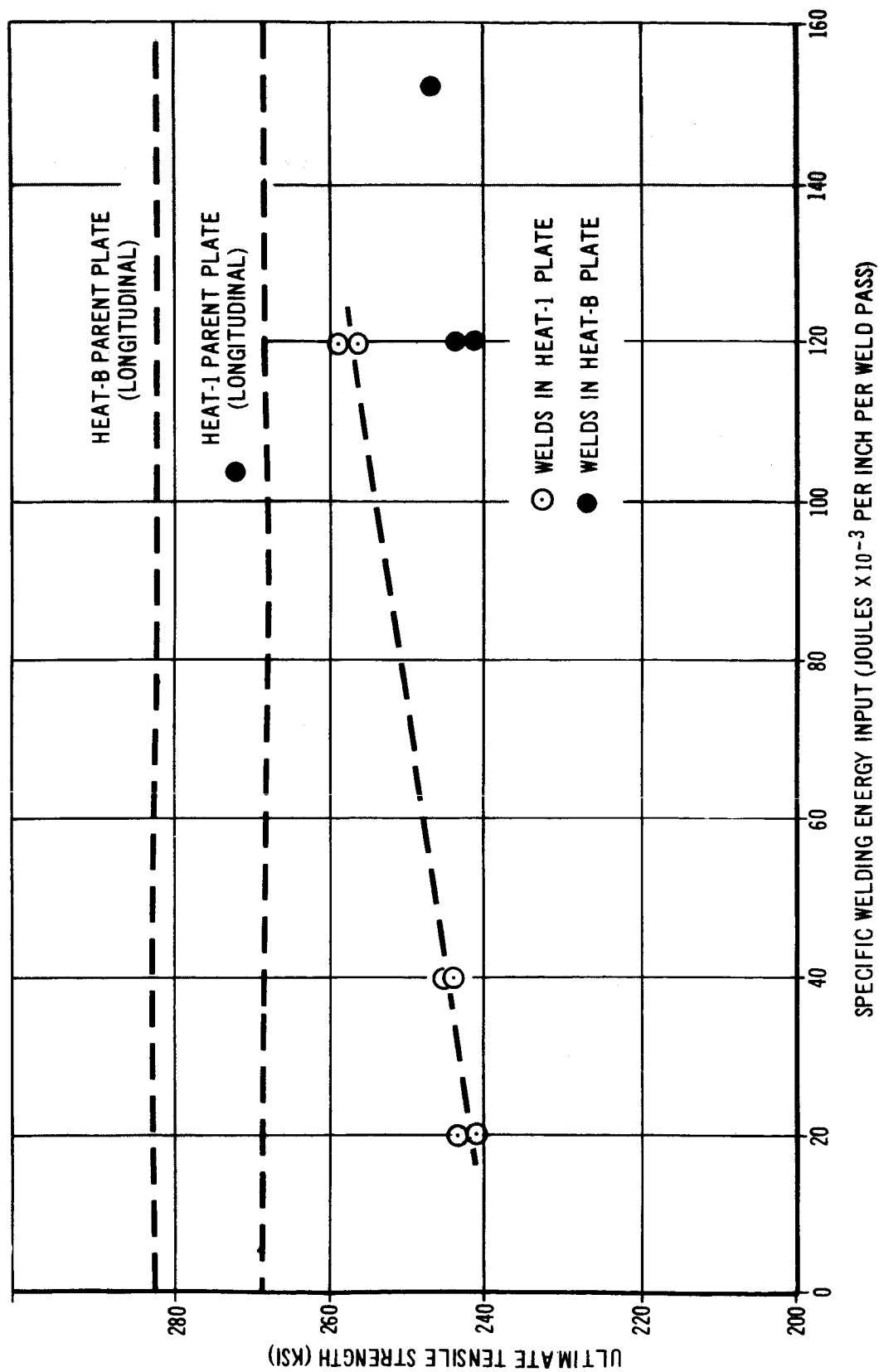
FIGURE 60
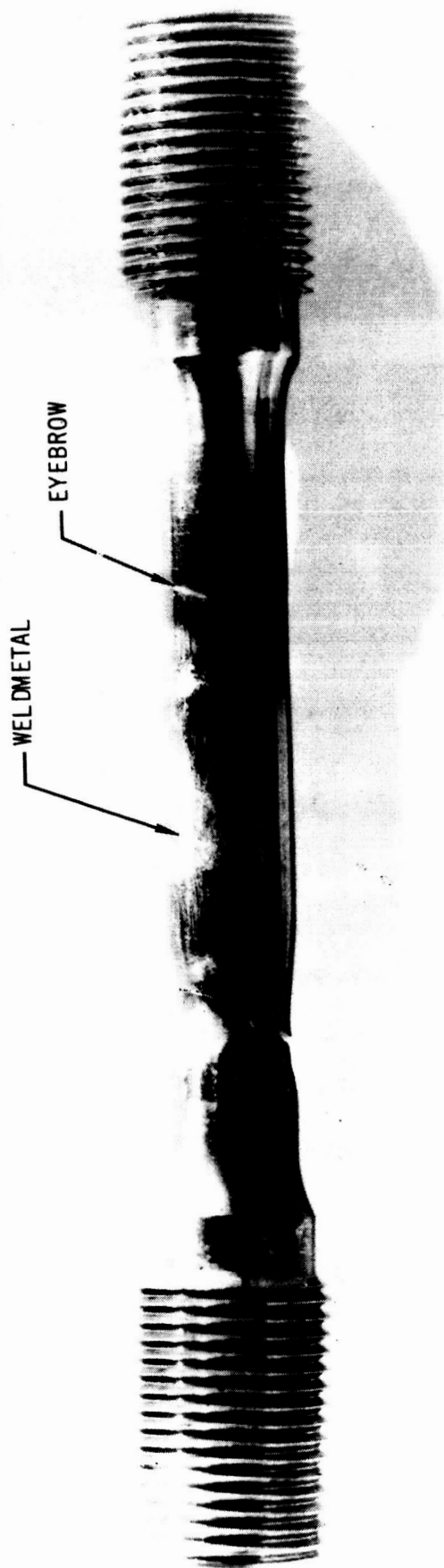
EYEBROW

WELDMETAL

ACROSS-THE-JOINT TENSILE SPECIMEN
ILLUSTRATING TYPICAL LOCATION OF TENSILE
FRACTURE IN VICINITY OF HEAT-AFFECTED ZONE EYEBROW

(SPECIMEN ETCHED TO DELINEATE WELDMETAL AND EYEBROW REGIONS)

FIGURE 61

EFFECT OF AGING TIME AT 875°F, 900, AND 950°F ON THE ACROSS-THE-JOINT TENSILE PROPERTIES OF TYPE W2 WELDS DEPOSITED IN HEAT-1 PLATE
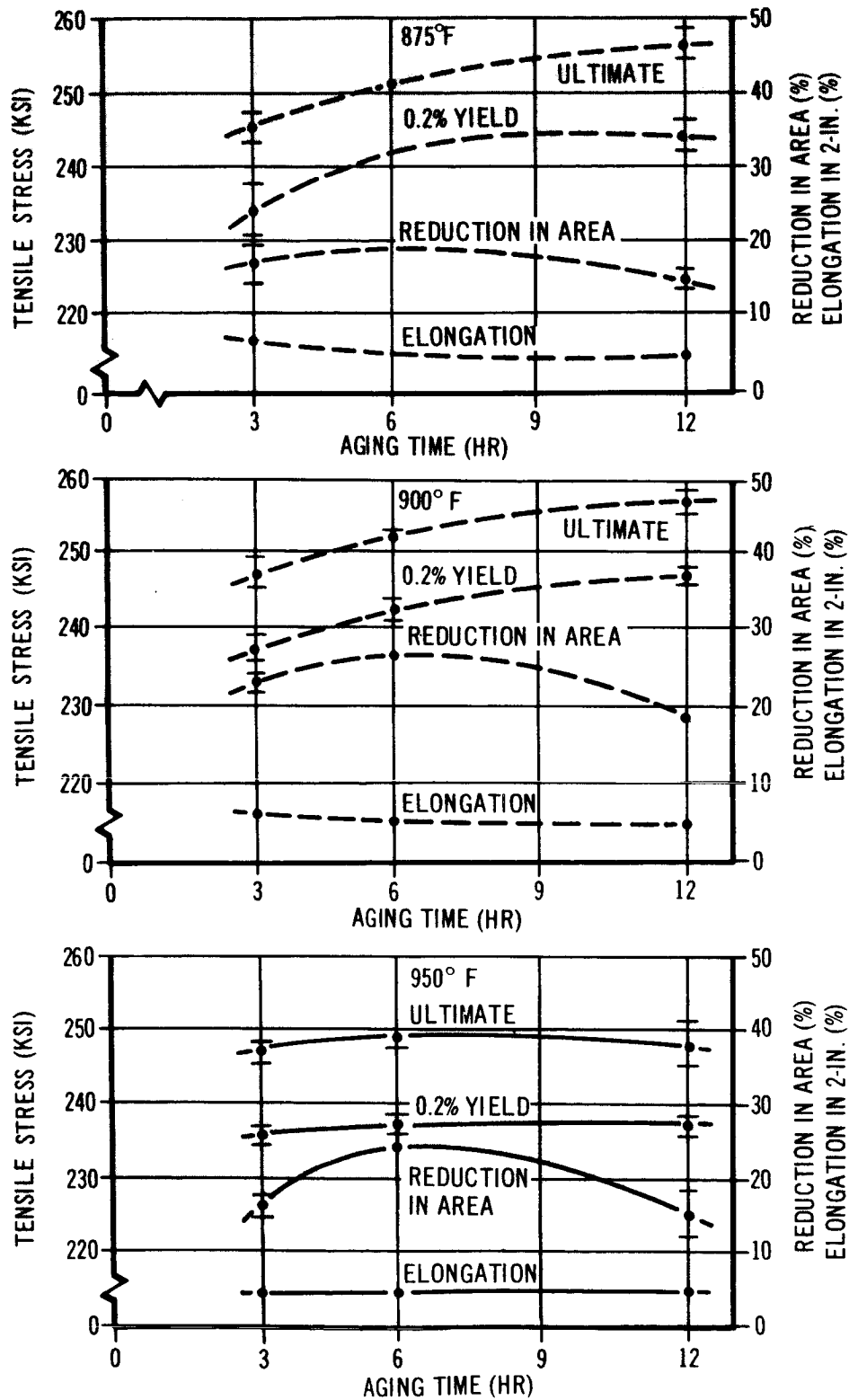
FIGURE 62

EFFECT OF AGING TIME AT 875°F ON THE ACROSS-THE-JOINT TENSILE PROPERTIES OF TYPES W-8 AND W-9 WELDS DEPOSITED HEAT-B PLATE

◆ ULTIMATE TENSILE STRENGTH
● 0.2% OFFSET YIELD STRENGTH
▲ % ELONGATION (IN 2 IN.)
■ % REDUCTION IN AREA
SOLID SYMBOLS — W9 TYPE WELDS
OPEN SYMBOLS WITH HORIZONTAL
TAILS — W8 TYPE WELDS

FIGURE 63

114
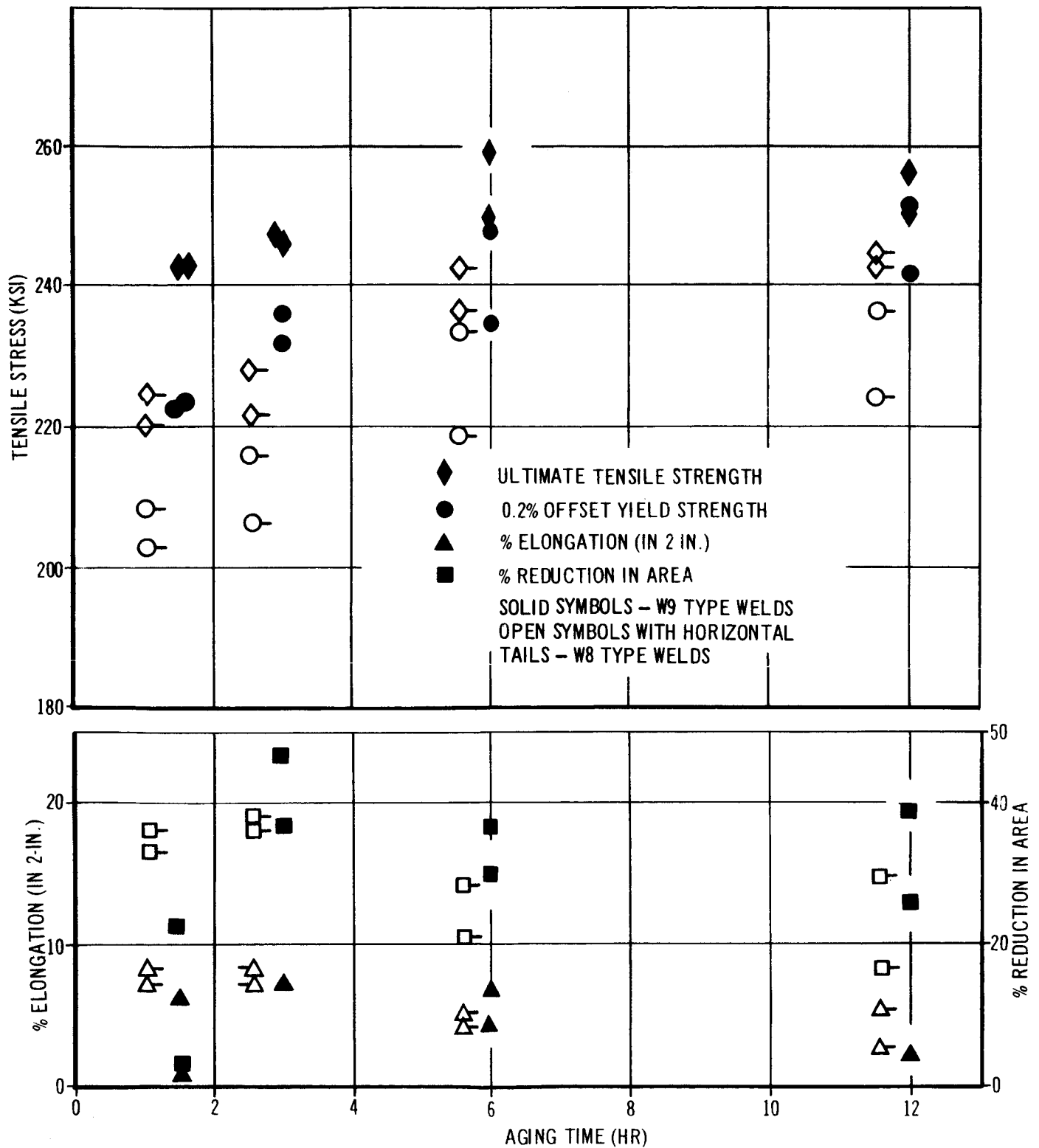
EFFECT OF AGING TIME AT 900°F ON THE ACROSS-THE-JOINT TENSILE PROPERTIES OF TYPES W-7, W8 AND W-9 WELDS DEPOSITED IN HEAT-B PLATE

Legend:
- ◆ ULTIMATE TENSILE STRENGTH
- ● 0.2% OFFSET YIELD STRENGTH
- ▲ % ELONGATION (IN 2 IN)
- ■ % REDUCTION IN AREA

SOLID SYMBOLS — W9 TYPE WELDS

OPEN SYMBOLS WITH TAILS — W8 TYPE WELDS

OPEN SYMBOLS — W7 TYPE WELDS

FIGURE 64

115
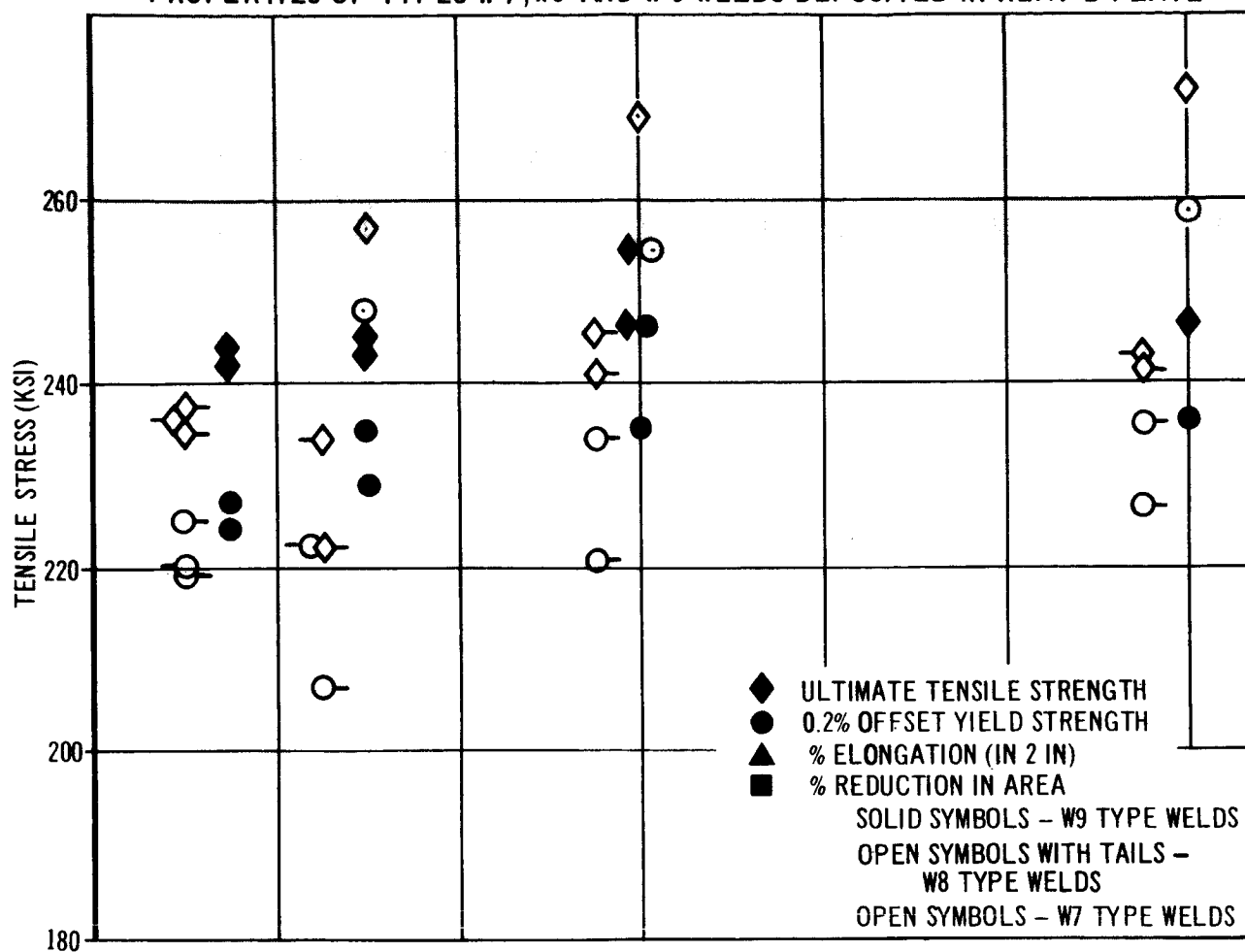
EFFECT OF AGING TIME AT 950°F ON THE ACROSS-THE-JOINT TENSILE
PROPERTIES OF TYPES W-7, W-8 AND W-9 WELDS DEPOSITED IN HEAT-B PLATE
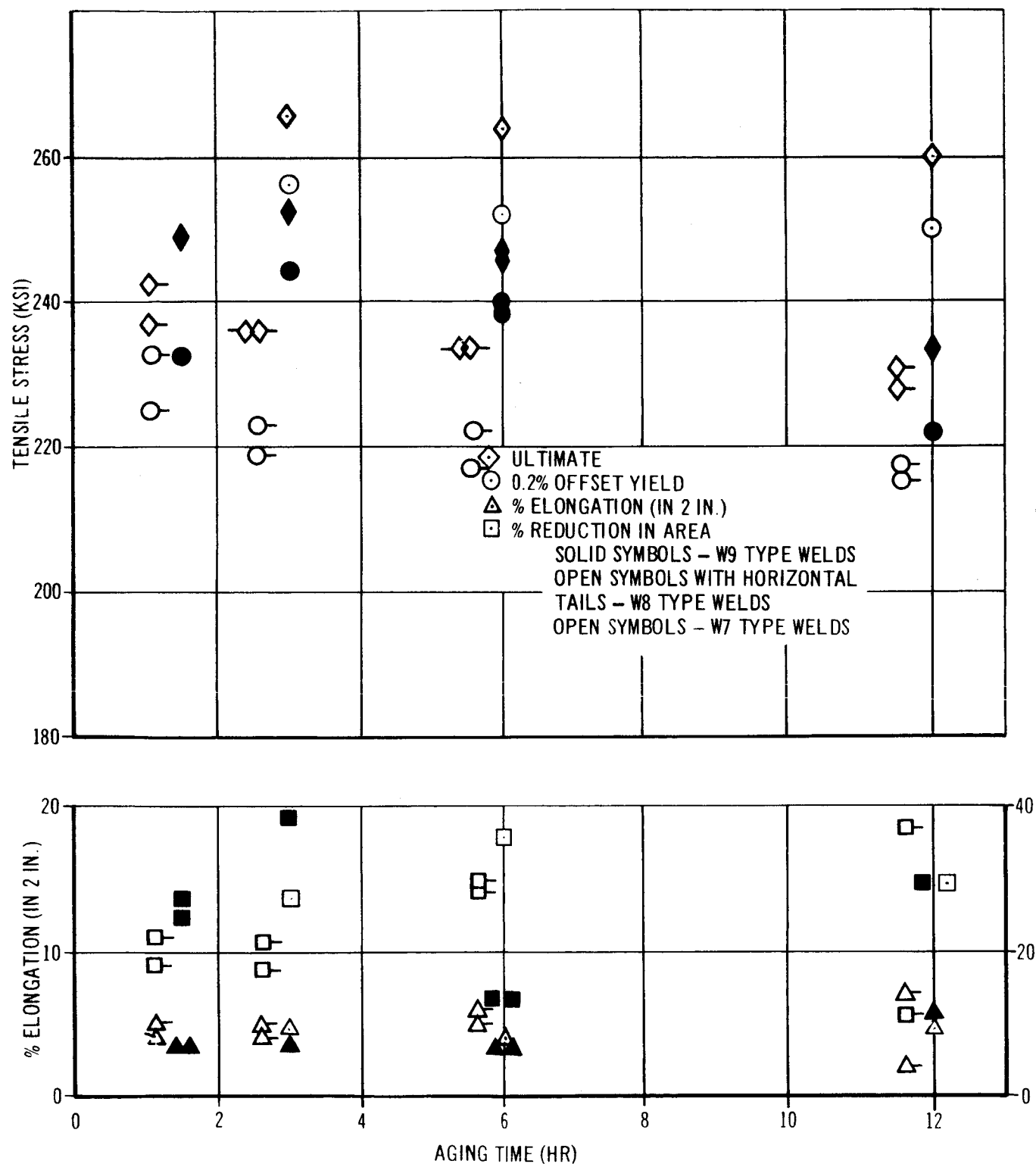
FIGURE 65

TABLE XIV   TENSILE PROPERTY DATA ON TYPES W7 AND W8 WELDS

10" x 3/4 x 3/4"   SPECIMENS

SPEC. NO.	WELD TYPE	PLATE CONDITION PRIOR TO WELDING	SPEC ORIEN-TATION	AGING TEMP. (°F)	AGING TIME (HRS)	0.2% YIELD STRENGTH (KSI)	ULTIMATE STRENGTH (KSI)	% ELONG (2- IN.)	REMARKS
6AW1	W7	As Rec'd.	L	900	3	245.8	264.5	7.0	J
6AW3	W7	Aged	L	900	3	252.7	263.9	5.5	
212A1	W8	As Rec'd.	L	900	3	255.0	258.0	7.0	
212B1	W8	As Rec'd.	L	900	3	262.0	267.0	8.0	
6AW2	W7	As Rec'd.	T	900	3	248.6	261.1	5.0	C
6AW4	W7	Aged	T	900	3	254.7	266.2	4.0	D
212A2	W8	As Rec'd.	T	900	3	243.0	247.0	5.0	C
212B2	W8	As Rec'd.	T	900	3	237.0	252.0	7.0	C

NOTES:

1. See Tables XI   for definition of weld types

2. Plate aged before welding was aged at 900°F for 3 hours

3. See Table XII   for definition of remark code numbers.

3.7.3   <u>Effects of Welding Procedure and Aging Heat Treatment On The Aging</u>
         <u>Response of Heat-Affected Regions</u> (Cont'd.)

         plate strength, with little loss in ductility.

3.8   <u>Effect of PTC Specimen Type and Orientation on the Net Fracture</u>
         <u>Stress of Weldmetal</u>

         As previously noted, during the initial stages of the 18Ni-7Co-5Mo

         maraging steel investigations at Douglas, a large (48" x 4" x 3/4")

         specimen was employed to measure the fracture toughness of the 3/4-

         inch thick plate and welds.

         Results described in a previous section demonstrated that 18Ni-7Co-

         5Mo plate fracture toughness data obtained with 8" x 11/16" x 5/16"

         PTC specimens was essentially equivalent to that obtained with 24"

         x 3" x 3/4" PTC specimens. Data already presented, demonstrated that

         we:dmetal would be expected to behave in a similar manner. This

         belief was further confirmed by tests performed on welds deposited

         in Heat B plate.

         Figure 66 illustrates the specimen orientations used for the determin-

         ation of weldmetal fracture toughness of deposits in Heat I plate.

         Figure 34 (section 2.9.2) compares results obtained with the two

         specimen types in evaluating the fracture toughness of type W2

         weldmetal (discussions concerning welding procedures and compositional

         effects will be presented in a later section).

         Figure 67 depicts data on types W7 and W8 deposits in Heat B plate.

         In addition to the two specimen orientations employed for welds in

         Heat I plate, a third orientation was employed. The third specimen

3.8   Effect of PTC Specimen Type and Orientation on the Net Fracture
        Stress of Weldmetal (Cont'd.)

        orientation consisted of a 8-in long, longitudinal, all weldmetal

        specimen. This type of specimen had to be machined to a thickness

        of 3/16-inch to assure an all-weldmetal coupon. The plane of the

        partial thickness crack is transverse to the longitudinal axis of

        symmetry of the weld and perpendicular to the plate surfaces.

        The results indicate that rather close correlation exists among the

        different specimen sizes and crack orientations. The results obtained

        with the nominally 8" × 11/16" × 5/16" PTC specimens, regardless of

        crack orientation, are substantially in agreement with those obtained

        with the larger full 3/4-inch thickness specimens. These results

        must be qualified, however, since the ratio of crack length to crack

        depth is about the same for the various specimen sizes and orienta-

        tions (crack length = 2 1/2 to 3 times depth; see Figure 37,

        Section 2.9.2). Had this not been the case, such good agreement

        would not have been obtained.

        As a result of these findings, the small 8" × 11/16" × 5/16" PTC

        specimen was employed, almost exclusively, for the remainder of the

        weld evaluations conducted in fulfillment of this contract.

3.9   Effects of Weld Deposit Chemical Composition, Welding Procedure,
        and Post-Weld Aging Treatment on Weldmetal Fracture Toughness

        This section summarizes experimental results concerning the depend-

        ence of weldmetal fracture toughness on a variety of welding,

        compositional and heat treatment variables. These observations,

PTC SPECIMENS AND CRACK LOCATIONS USED FOR WELDMETAL FRACTURE TOUGHNESS EVALUATIONS

(CRACK PLANE PERPENDICULAR TO
PLATE SURFACES AND COPLANAR
WITH LONGITUDINAL PLANE OF SYMMETRY OF WELD)

FIGURE 66

EFFECT OF PTC SPECIMEN TYPE AND ORIENTATION ON THE NET FRACTURE STRESS OF WELDMETAL DEPOSITED IN HEAT-B PLATE

8" × 11/16" × 3/16" (○)
24" × 3" × 3/4" (◇)
8" × 11/16" × 5/16" (□)

900°F, 3 HR.

OPEN SYMBOLS – W7
SOLID SYMBOLS – W8

CRACK DEPTH (IN.)

NET FRACTURE STRESS (KSI)

FIGURE 67

121
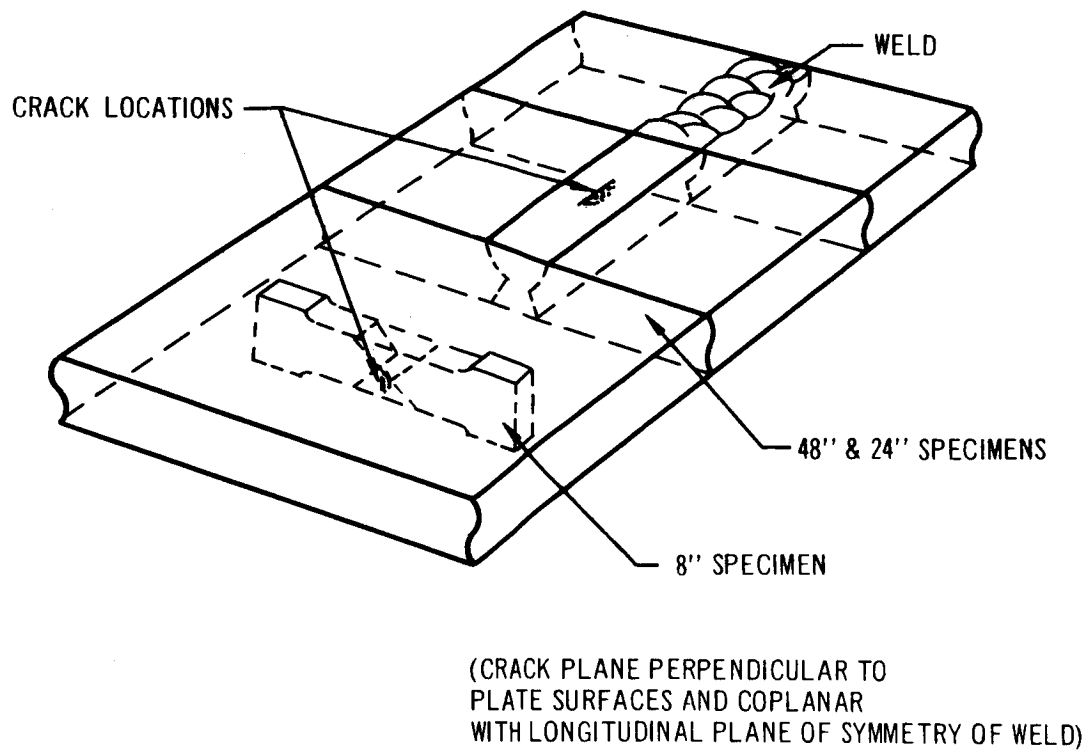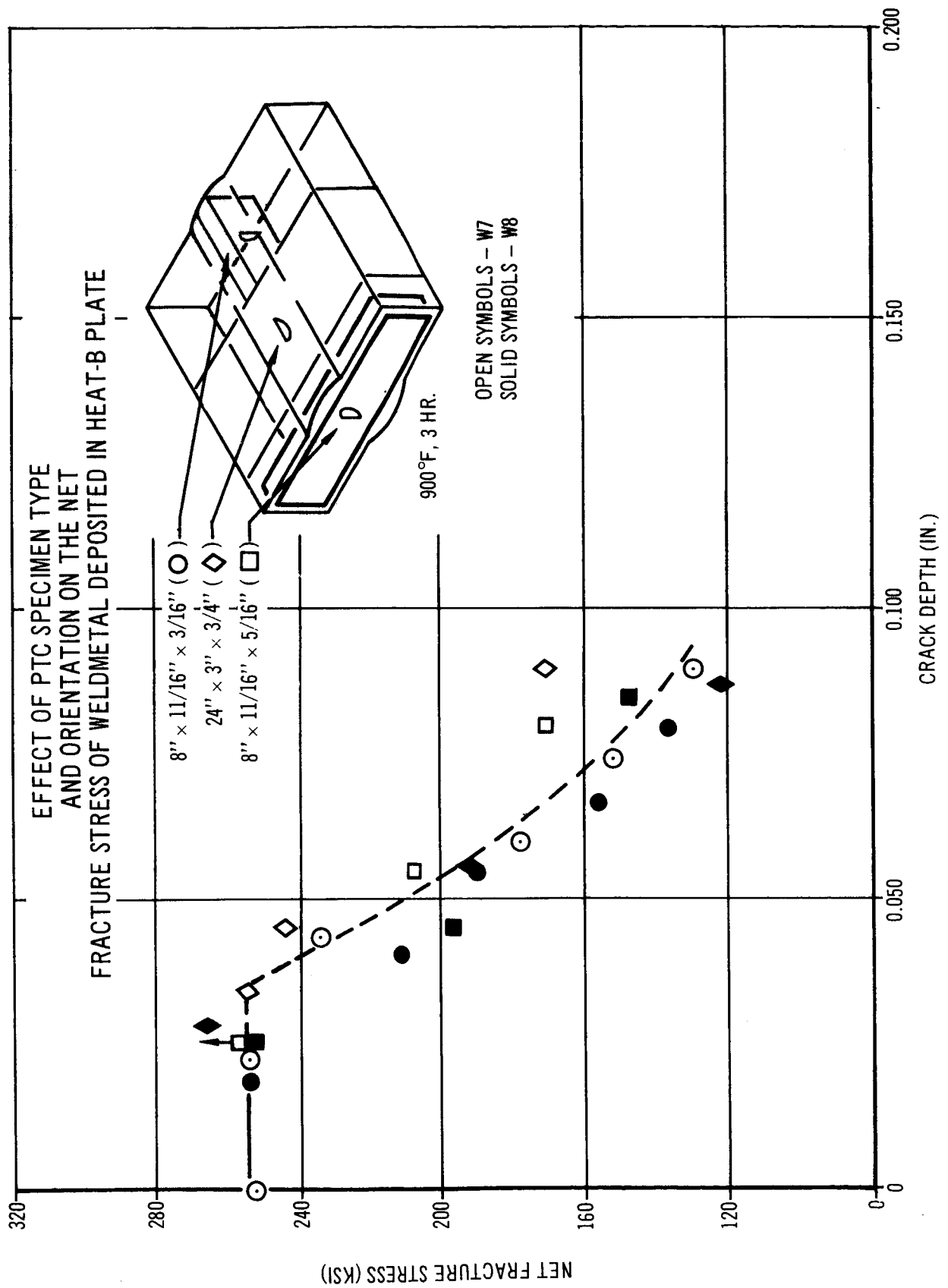
viewed in relationship to the metallurgical observations described
in a later section, permit the formulation of an hypothesis relating
the cause of inferior weldmetal toughness to a possible microstructur-
al invariant.

3.9.1   Welds in Heat I Plate

As may be seen from the tabulated characteristics in Table XI,
Section 3.2, the welding procedures included principally two-pass
MIG deposited welds (about 120,000 joules per inch of weld per weld
pass). However, multipass MIG (about 50,000 joules per inch of
weld per weld per weld pass) and electron beam welds (about 20 joules
per inch of weld) are also included. Figures 68 through 71 illus-
trate typical macrosections of some of the types of welds presented
in Table XI. The differences in gross macrostructure are clearly
evident. The two pass welds (Figures 70 and 71) are characterized
by a pair of intersecting "eyebrows" which demark regions of
partially reverted and retained austenite. The multipass welds
(Figure 69) exhibit a multitude of intersecting "eyebrows", whereas
the electron beam weld (Figure 68) exhibits single eyebrow parallel-
ing each fusion line.

Figure 72 depicts the net-fracture strength characteristics for the
various types of welds deposited in Heat I plate. The plane of the
partial thickness cracks is illustrated in Figure 72, along the
longitudinal axis of symmetry of the weld deposit and perpendicular

3.9.1   Welds in Heat I Plate (Cont'd.)

to the original plate surface. Post-weld aging treatments of 3
hours duration at 900°F appear to be somewhat less damaging than
those of 12 hours duration. Because of the limited data, decisive
conclusions concerning the effects of aging time cannot be stated.
By comparing Figure 72 to Figure 28 (Section 2.8.3) (pertaining to
Heat I plate), the weld deposits are observed to be substantially
inferior to the parent plate. For example, the critical crack depth
for Heat I plate and weld deposits in Heat I plate are about 0.100
and 0.035 inches, respectively. A most striking observation, how-
ever, is that despite the different welding procedures and weld
deposit chemical compositions, the dependence of net fracture strength
on crack size remains substantially constant (i.e., approximately
constant $K_{IC} \approx 55-70$ KSI$\sqrt{in}$, See Appendix IX).   Furthermore, the
differences in the specific welding energy inputs used in depositing
the welds evaluated produce vastly different rates of solidification.
Consequently, these observations also indicate that the rate of
weldmetal solidification and the attendant differences in solidifica-
tion pattern (partially illustrated in Figures 6ʊ i.ʃ 70), weld
deposit grain size (prior austenitic grain size), and dendrite cell
size have little, if any, effect on weldmetal toughness.

3.9.2   Welds in Heat B Plate

The rather surprising relative invariance of fracture toughness of
weldmetal was again demonstrated by an evaluation of weld deposits
in Heat B plate. Types W7 and W8 welds were evaluated using
8" x 11/16" x 5/16" PTC specimens. The partial cracks were located
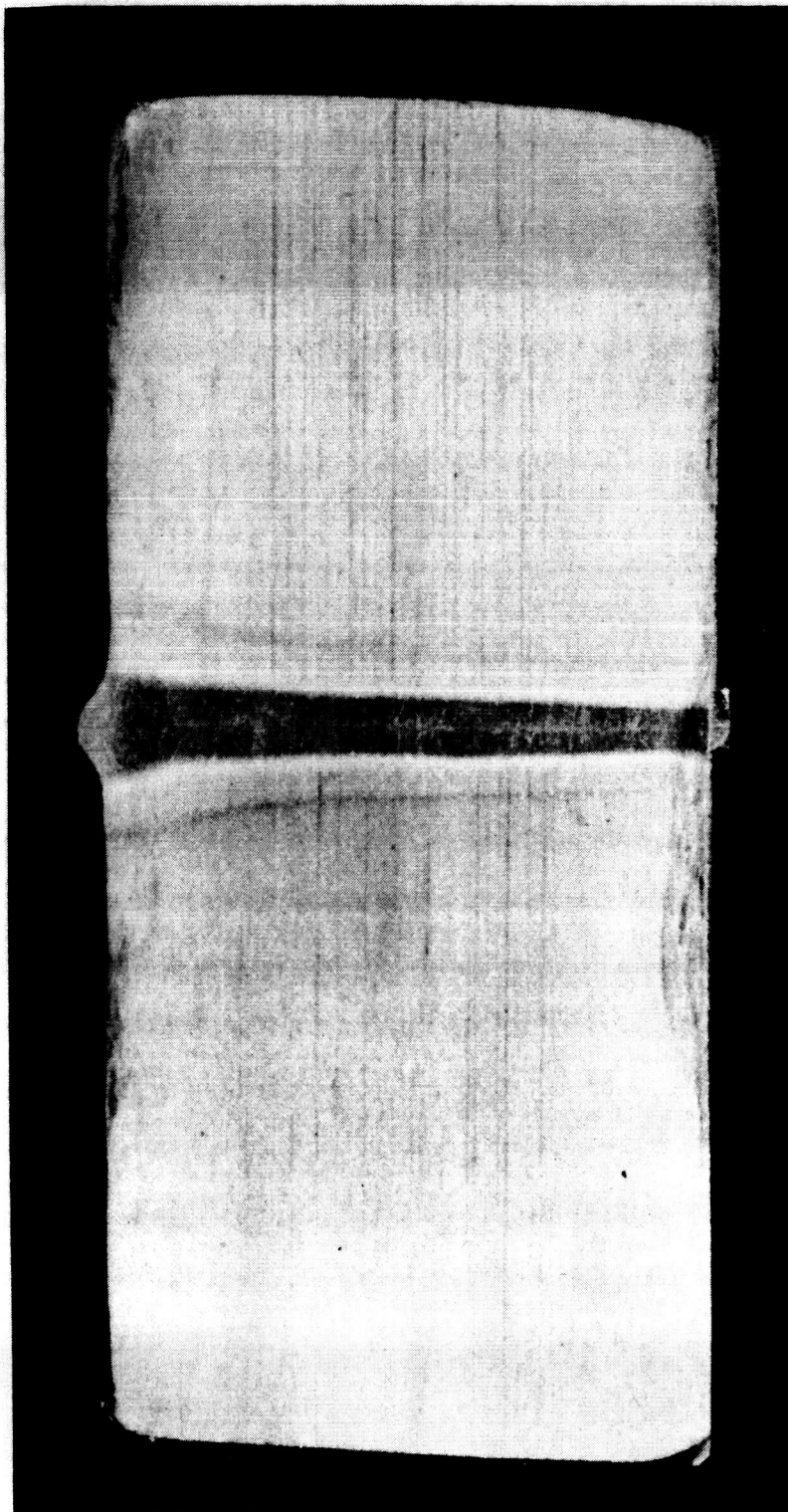
MACROSECTION OF TYPE W6 WELD
(20,000 JOULES PER INCH OF WELD).
ETCHED WITH CARAPELLAS REAGENT 4X

FIGURE 68
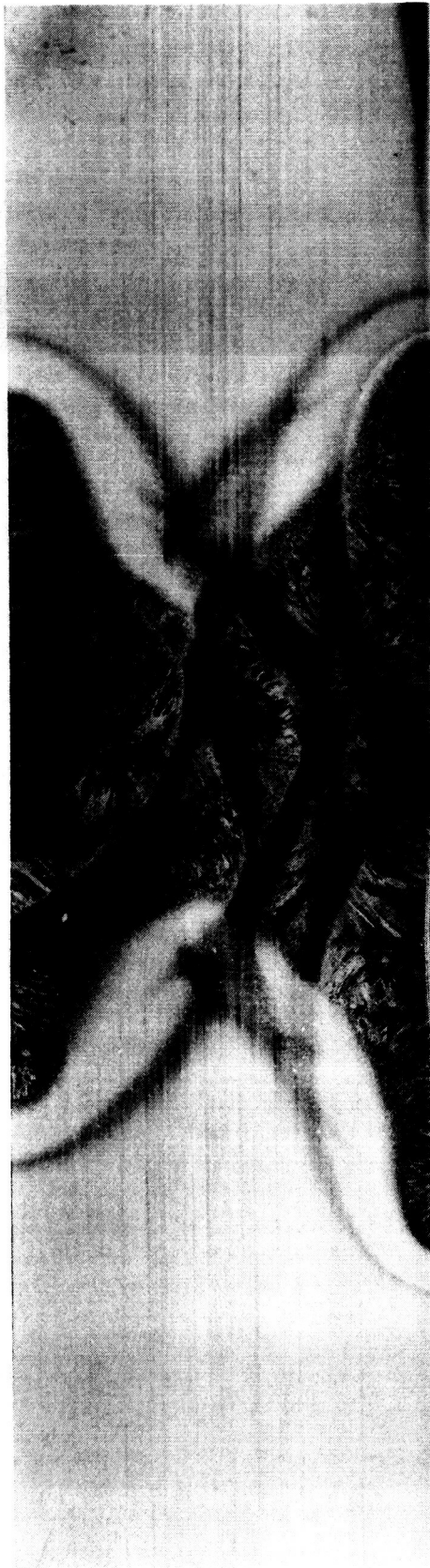
MACROSECTION OF TYPE W4 WELD
(40,000 JOULES PER INCH OF WELD PER PASS).
ETCHED WITH CARAPELLAS REAGENT. APPRX 3X.

FIGURE 69
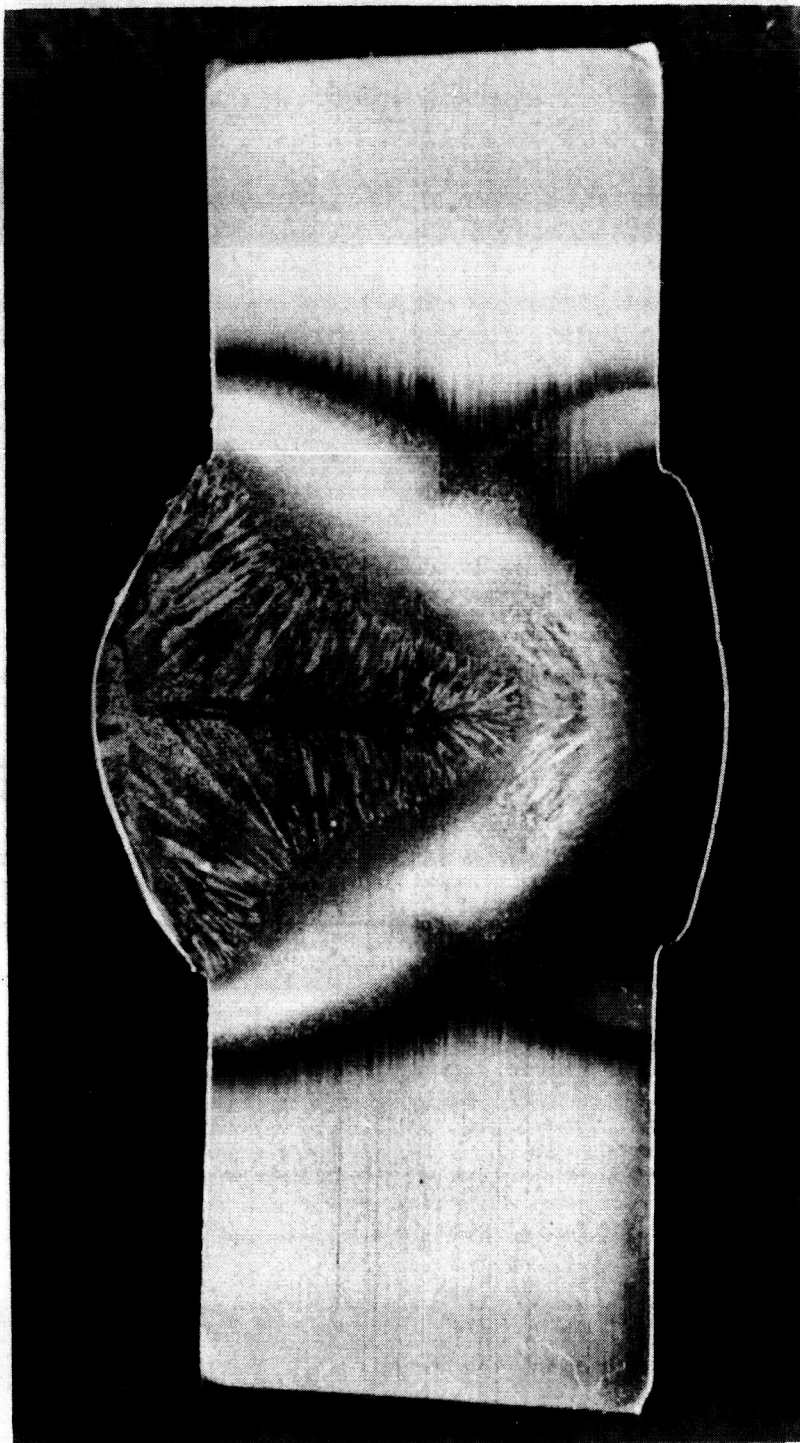
MACROSECTION OF TYPE W7 WELD
(120,000 JOULES PER INCH OF WELD PER PASS).
ETCHED WITH CARAPELLAS REAGENT. APPRX 3X

FIGURE 70
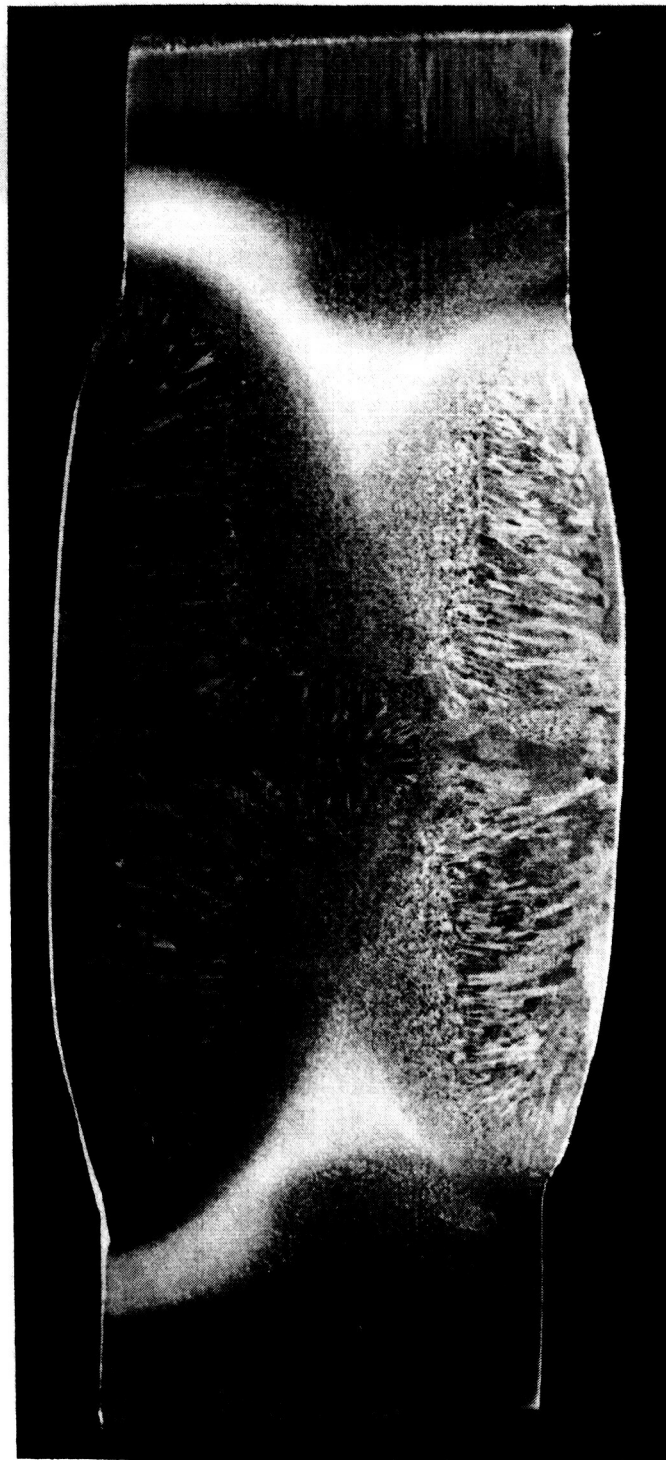
MACROSECTION OF TYPE W9 WELD
(150,000 JOULES PER INCH OF WELD PER PASS).
ETCHED WITH CARAPELLAS REAGENT.   APPRX 3X

FIGURE 71

EFFECT OF WELDMETAL COMPOSITION AND DEPOSITION TECHNIQUE ON THE NET FRACTURE STRENGTH OF WELD DEPOSITS IN 3/4"-18 Ni-7Co-5 Mo AIRMELTED STEEL (HEAT 1)

8" X 1/2" X 1/8" PTC SPECIMEN

ARROWS DENOTE FRACTURES
AWAY FROM CRACK

WELD PROC. & COMPOSITION CODE	POST WELD AGING TREATMENT	
	900°F 3 HRS	900°F 12 HRS
W1		●
W2	⊙	◆
W3	▣	
W4	◇	
W5		◆
W6		▲

NET FRACTURE STRESS (KSI)

CRACK DEPTH (IN)
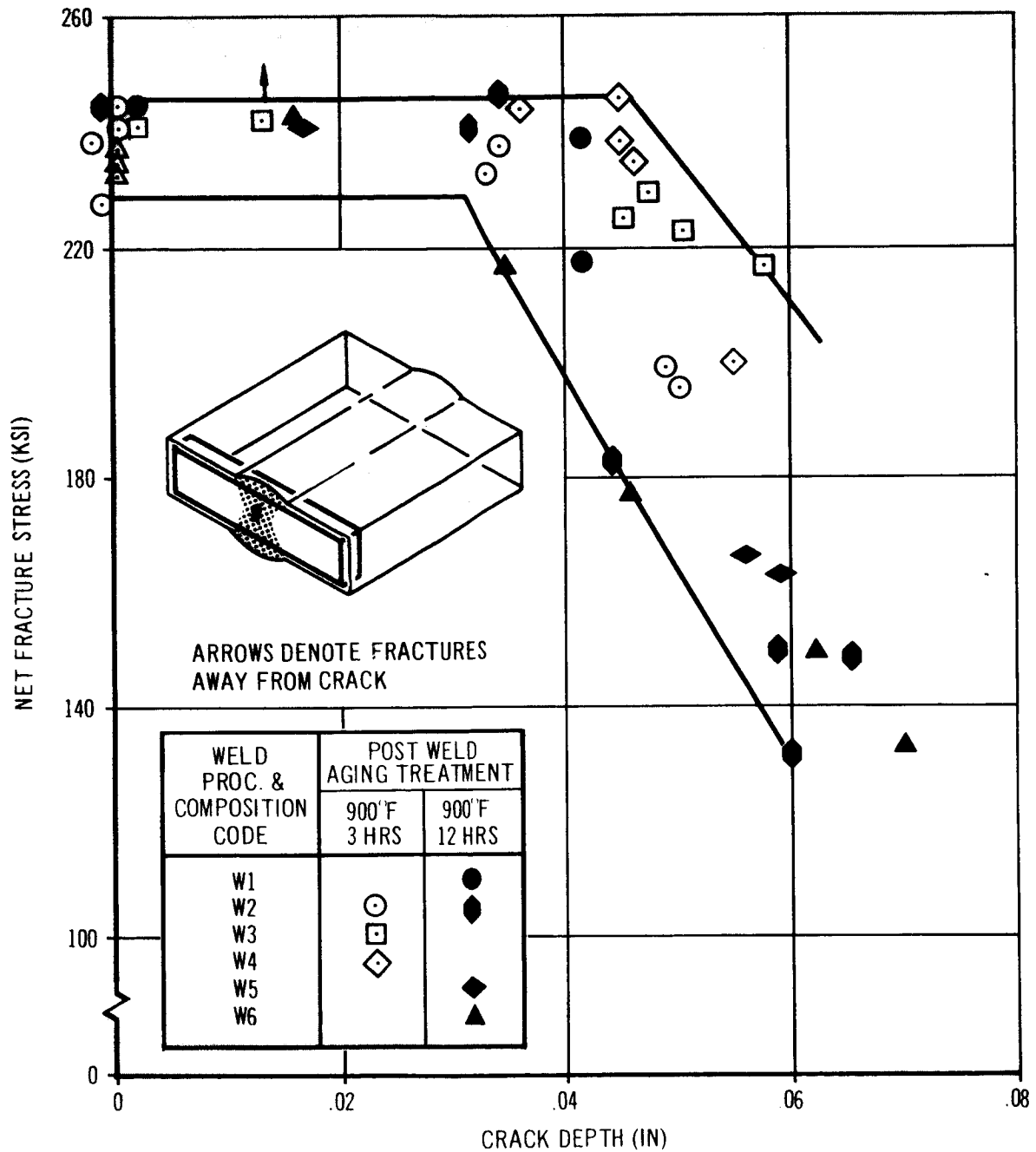
FIGURE 72

3.9.2   Welds In Heat B Plate

as illustrated, entirely within weldmetal. The crack plane was
perpendicular to the plate surfaces and coplanar with the longitud-
inal plane of symmetry of the weld. Figures 73 through 75 depict
the dependence of weldmetal net-fracture stress on post-weld aging
treatment (for times ranging from 1-1/2 to 12 hours at 875, 900,
950°F ± 5°F) for the two types of welds. The data are summarized
in Appendix IX. The results obtained with the two types of welds
are in good agreement. Comparison of the longest (6 and 12 hours)
exposure to the shortest (1-1/2 and 3 hours) indicates that some
degradation does occur upon prolonged aging especially at 875 and
900°F. This latter point is further demonstrated by Figures 76
through 78 in which K_{IC} (calculated on the basis of net fracture
stress as described earlier) is plotted as a function of aging time.
Plane-strain fracture toughness, K_{IC}, tends to decrease somewhat
with increasing aging time (especially at 875°F and 900°F),
although the changes are small. The striking observation, as for
the weld deposits in Heat I plate, is the relative constancy of
fracture toughness properties. This very significant point is
elaborated upon in subsequent sections where metallurgical observa-
tions are related.

Considering these fracture toughness data along with the all weld-
metal tensile data presented in a previous section, the following
observations may be made: (a) the metallurgical changes (precipita-
tion, ordering, and possibly austenite reversion) responsible for
producing substantial tensile strength and hardness changes during

3.9.2   <u>Welds in Heat B Plate</u>, (Cont'd.)

aging do not produce proportional concomitant changes in plane-strain fracture toughness, K_{IC}. (b) Ductility and plane-strain fracture toughness tend to remain relatively invariant over a wide range of aging temperature and times. These two observations suggest that the principal metallurgical factors influencing toughness and ductility properties are different from those which are responsible for the strengthening and hardening kinetics. One must conclude either that some microstructural invariant is responsible for the relative constancy of toughness and ductility, or that complicated compensating mechanisms are interacting. Metallurgical observations related in a later section favor the former conclusion.

3.9.3   <u>Effect of Re-Solution Heat Treatments on Weldmetal Toughness</u>

A limited evaluation of the effect of re-solution heat treatment prior to aging on weldmetal toughness has been undertaken (reference 7). Type W2 welds were re-solution heat treated at 1500^OF for one hour following welding and then aged at 900^OF for three or 12 hours. Plane strain fracture toughness was evaluated using the 8" x 1/2" X 1/8" PTC specimen. Figure 79 shows the effects of re-solution treatment on the net-fracture stress behavior. Re-solution heat treatment failed to improve fracture toughness, and for the 12 hour 900^OF aging treatment produced some additional degradation. Thus, once again relative constancy is demonstrated in fracture behavior. This further suggests that some "microstructural invariant" may be responsible for the inferior toughness properties of weldmetal.

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DEPENDENCE OF NET-FRACTURE STRESS ON CRACK DEPTH FOR WELDMETAL AGED AT 875° F FOR TIMES RANGING FROM 1 1/2 TO 12 HOURS. WELD DEPOSITS IN HEAT-B PLATE

⊙ 1 1/2 HR.   ◇ 6 HR.
▫ 3 HR.   △ 12 HR.

ARROWS DENOTE FRACTURES AWAY FROM CRACK

OPEN SYMBOLS - W7
SOLID SYMBOLS - W8

NET FRACTURE STRESS (KSI)

CRACK DEPTH (IN.)

FIGURE 73

131
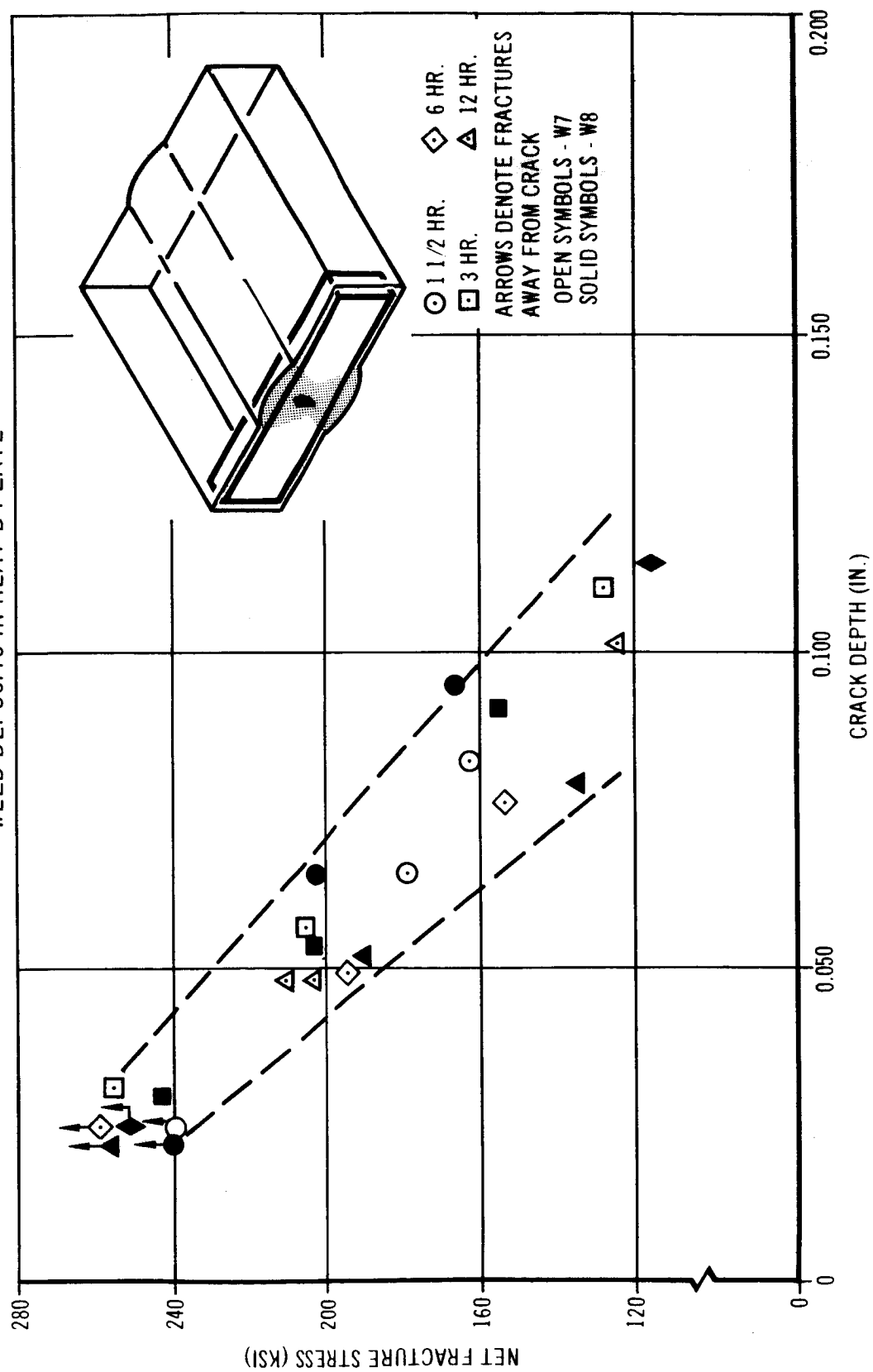
DEPENDENCE OF NET-FRACTURE STRESS ON CRACK DEPTH
FOR WELD METAL AGED AT 900° F FOR TIMES RANGING FROM
1 1/2 TO 12 HOURS WELD DEPOSITS IN HEAT-B PLATE

FIGURE 74

132
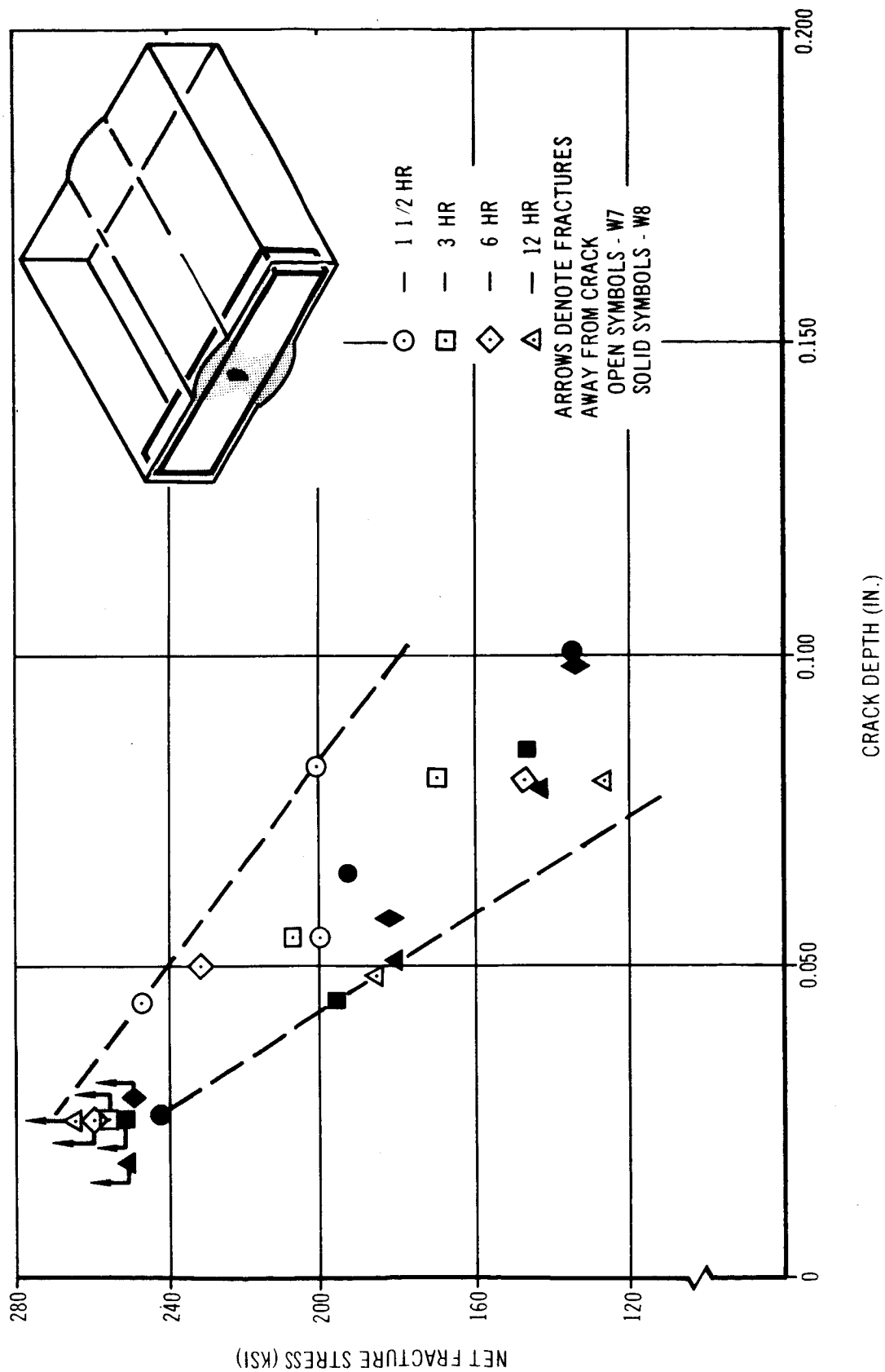
DEPENDENCE OF NET-FRACTURE STRESS ON CRACK DEPTH FOR WELD METAL AGED AT 950° F FOR TIMES RANGING FROM 1 1/2 TO 12 HOURS. WELD DEPOSITS IN HEAT-B PLATE

OPEN SYMBOLS - W7
SOLID SYMBOLS - W8

⊙ 1 1/2 HR.
□ 3 HR.
◇ 6 HR.
△ 12 HR.

ARROWS DENOTE FRACTURES AWAY FROM CRACK

CRACK DEPTH (IN.)

NET FRACTURE STRESS (KSI)
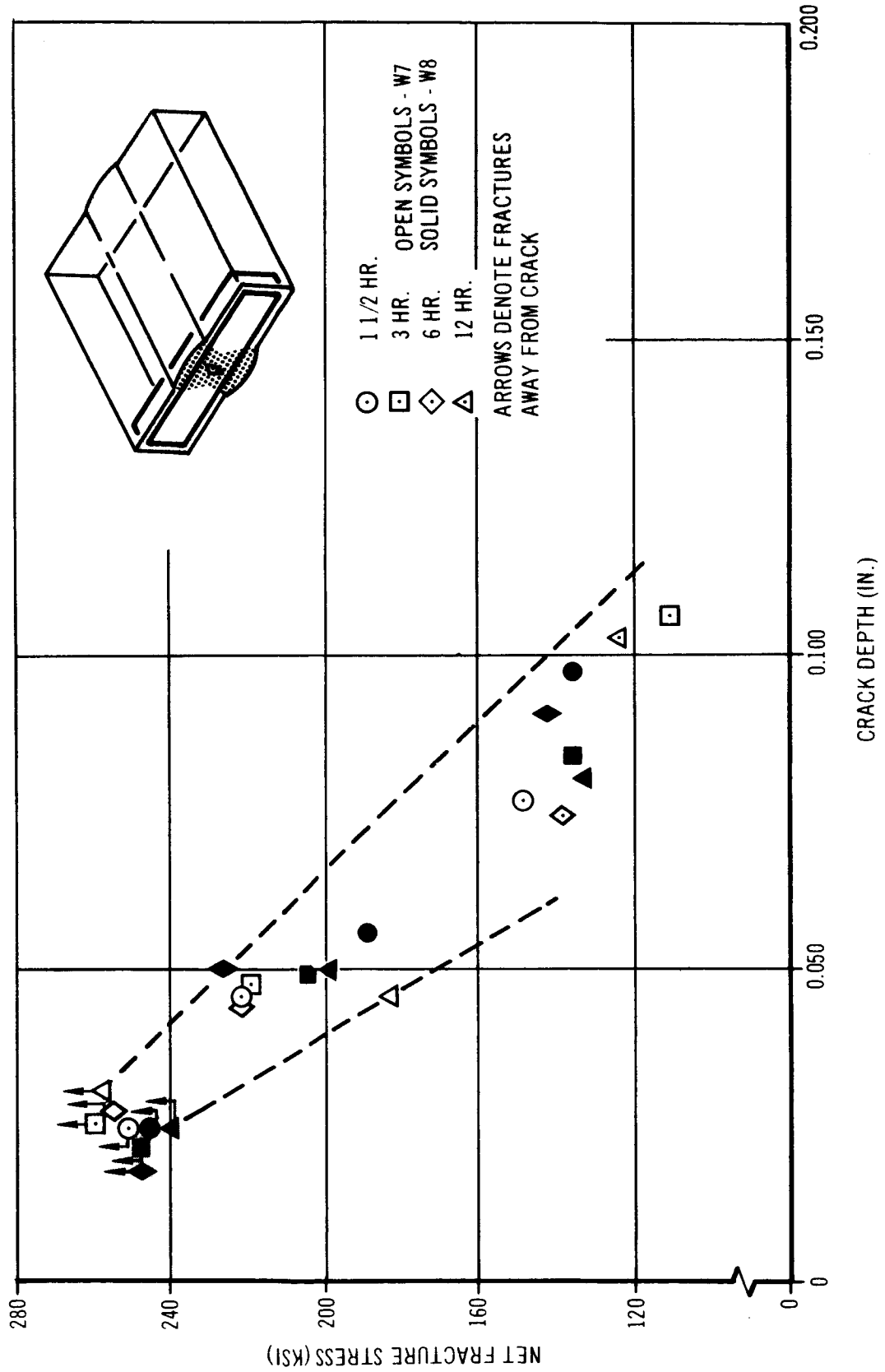
FIGURE 75

EFFECT OF 875°F AGING TIME ON K_{IC} OF
WELDMETAL DEPOSITED IN HEAT-B PLATE
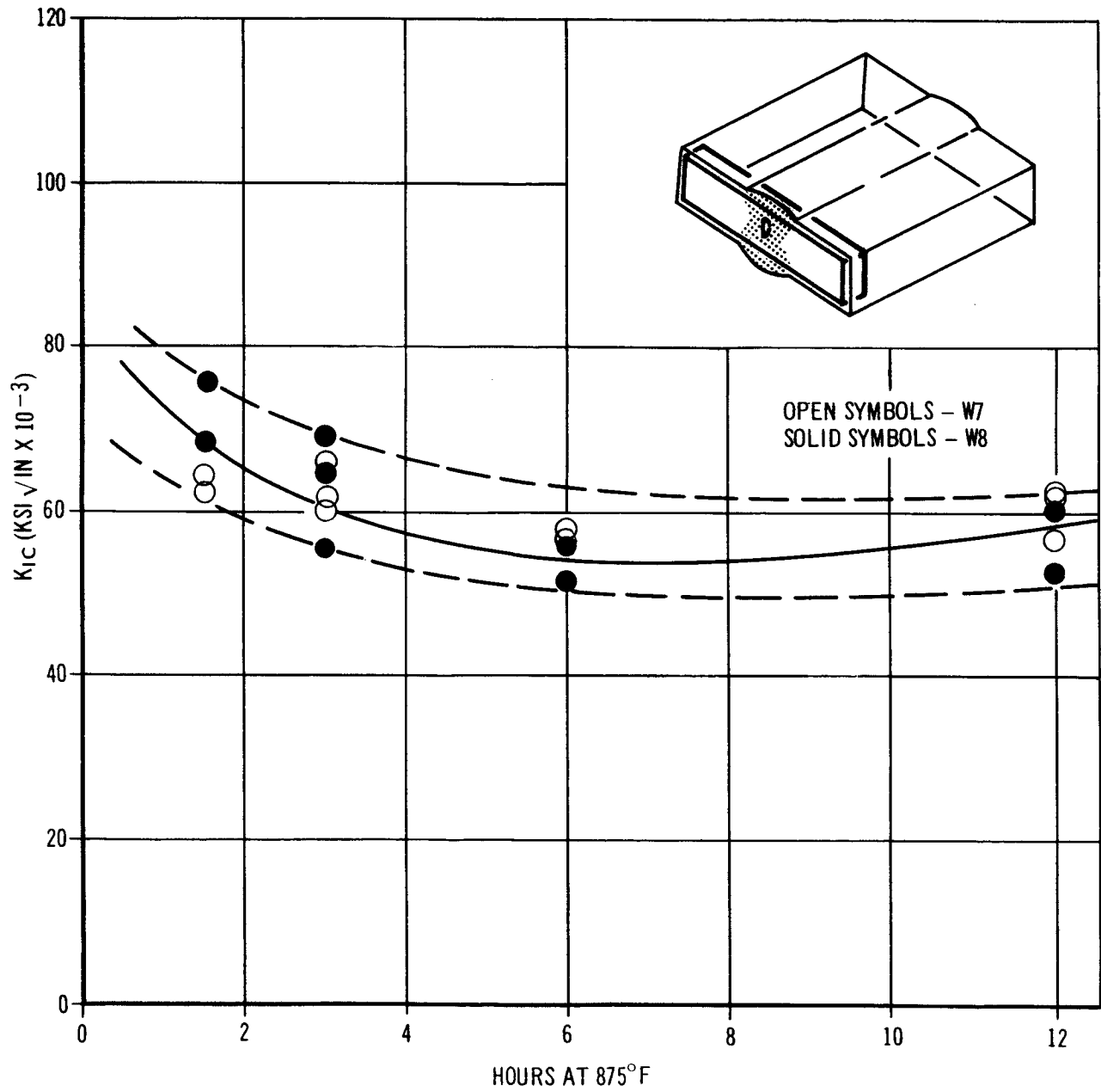
FIGURE 76

EFFECT OF 900°F AGING TIME ON K_{IC} OF
WELDMETAL DEPOSITED IN HEAT-B PLATE
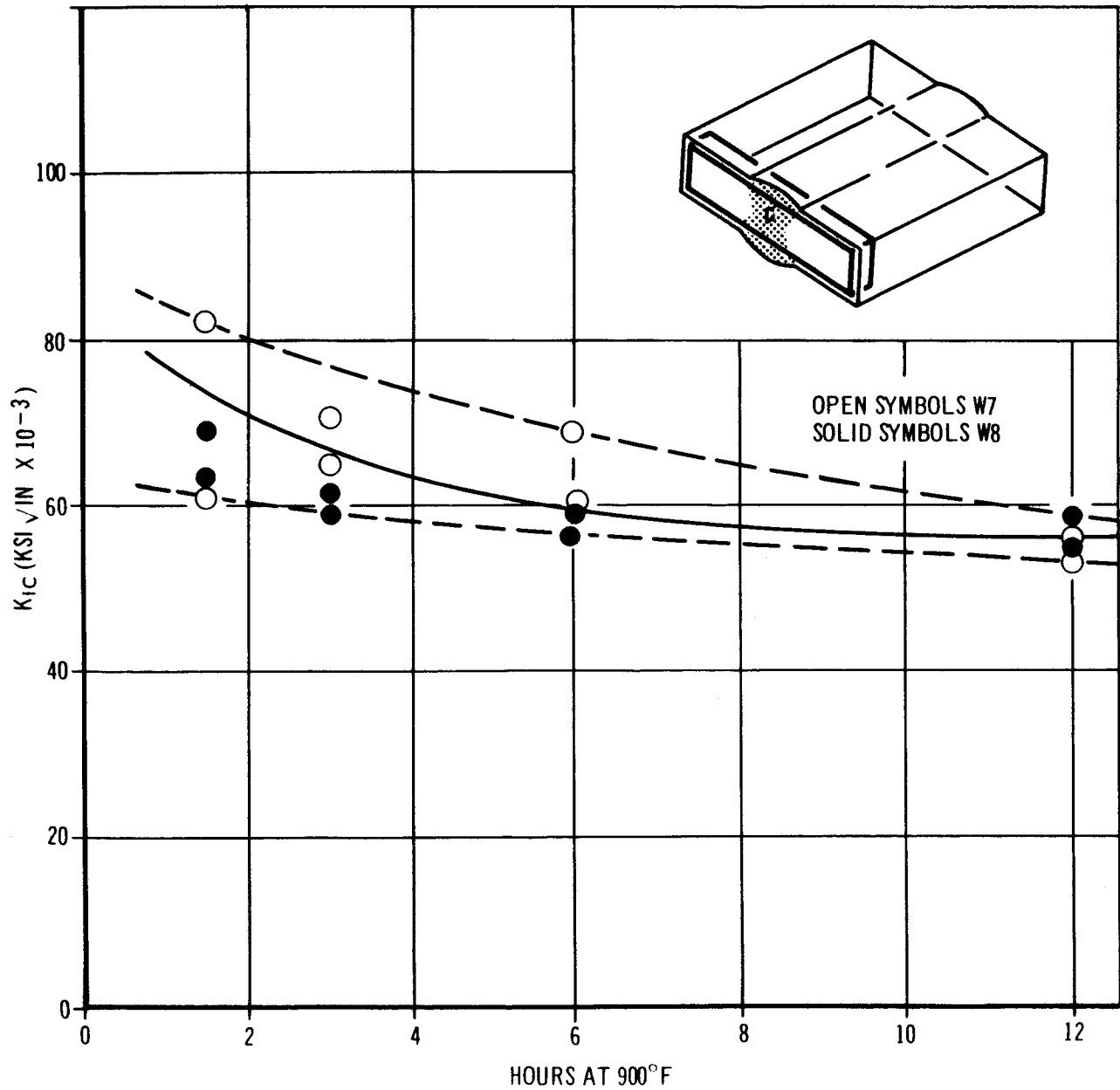
FIGURE 77

EFFECT OF 950°F AGING TIME ON K_{IC} OF
WELDMETAL DEPOSITED IN HEAT-B PLATE

OPEN SYMBOLS – W7
SOLID SYMBOLS – W8

K_{IC} (KSI $\sqrt{IN}$ X 10 $^{-3}$)

HOURS AT 950°F
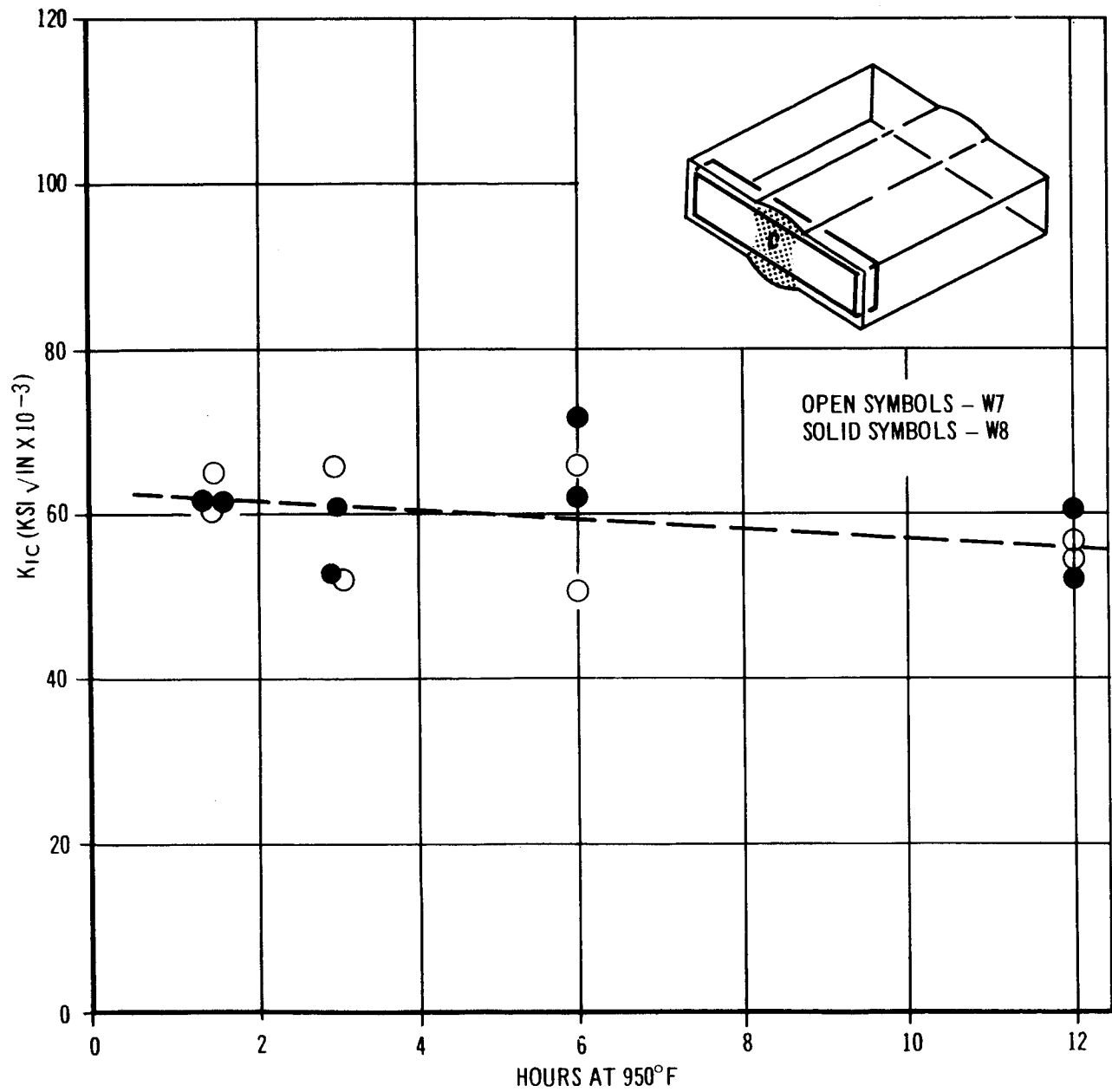
FIGURE 78

EFFECT OF CRACK DEPTH ON THE NET
FRACTURE STRENGTH OF WELDMETAL AS
INFLUENCED BY RE-SOLUTION HEAT TREATMENT

8" X 1/2" X 1/8" PTC SPECIMEN   W2 TYPE WELDS
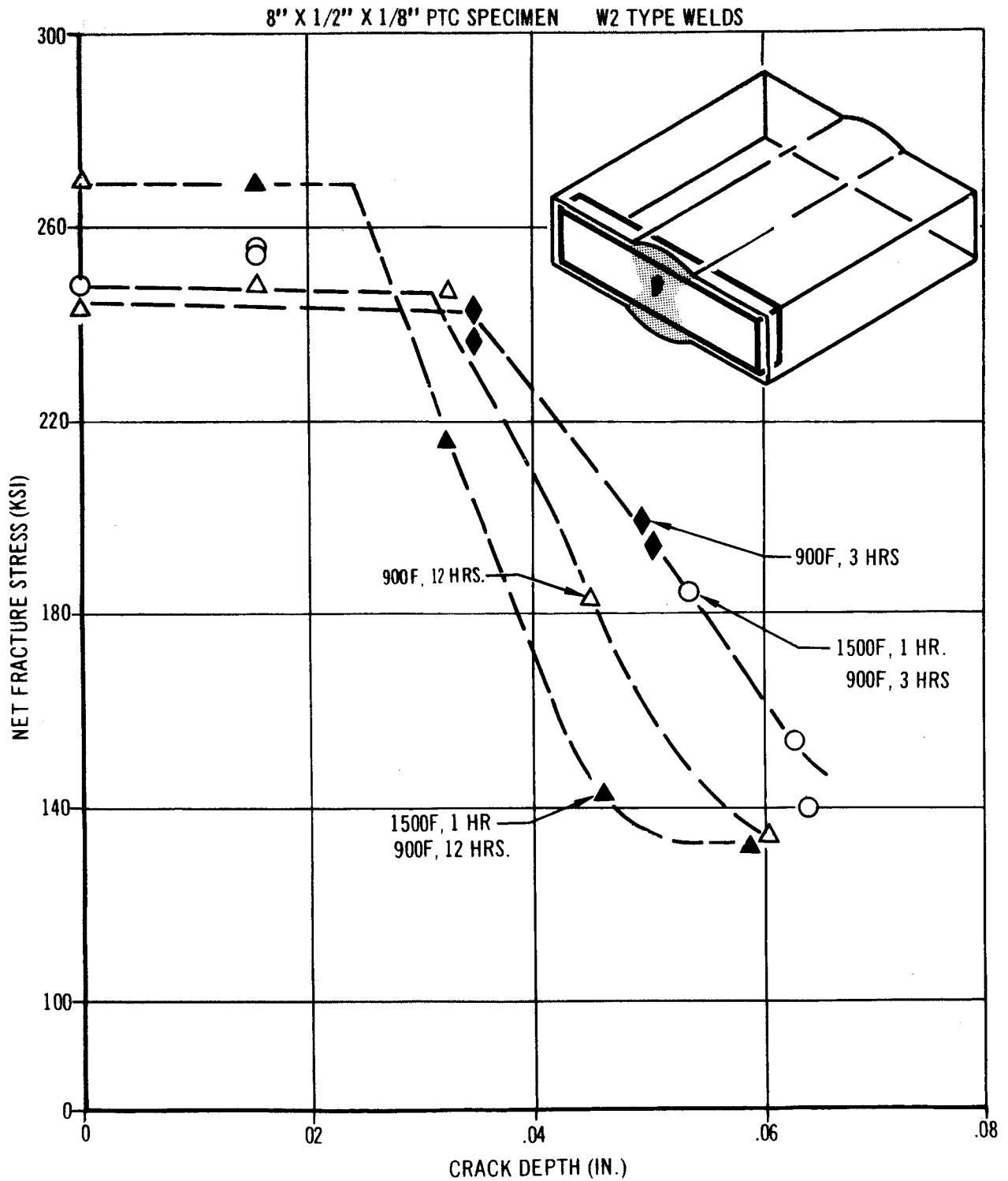
FIGURE 79

3.10   Fracture Toughness of Plate Heat-Affected Regions

This section presents data concerning the fracture toughness behavior of plate heat-affected zones. Heat-affected zone toughness deficiencies do not appear to be nearly as important a problem area as those represented by weldmetal toughness. However, metallurgical data to be presented in a subsequent section demonstrate that toughness impairment in both weldmetal and heat-affected regions could be produced by the same factors.

Figures 80, 81, and 82 depict net fracture strength behaviors for heat-affected regions in type W7 weldments in Heat B plate. Tabulated data are presented in Appendix V. Two crack propagation directions with respect to plate rolling direction and three specimen orientations were employed as illustrated in the figures. The weldments were subjected to postweld aging at $900^\circ F$ for 3 hours.

Plane strain fracture toughness values, K_{IC}, are denoted in parentheses for applicable points. There are some difficulties involved in the interpretation of these data. First, crack propagation does not occur through a single microstructural region, but rather through a microstructural composite (the cracks were generally confined near coarse-grained regions and every effort was made to avoid the reverted austenite region). Second, the crack could not be identically located in all specimens. As a result of these limitations, some scatter would be anticipated. For the most part the results do not differ significantly from those obtained on parent plate for the same aging heat treatments (see Figure 36, Section 2.9.2

and identical specimen orientations).

The data do not disclose any striking deficiencies in heat-affected zone toughness, although some scatter does prevail especially for the Figure 82 data. Some of the scatter is undoubtedly due to the limitations previously discussed. However, several rather low K_{IC} values are apparent (especially the $K_{IC} = 63$ KSI$\sqrt{in}$) for the specimens depicted in Figure 82 for which the crack propagation direction is parallel to the rolling direction. It would be unwarranted to attach much importance to these few low points on the basis of such limited data. However, metallurgical observations related in later sections lend support to the contention that degraded toughness may indeed prevail in some heat-affected regions. As will be seen, the possible degradation does not appear to be related to the heat affects of welding as much as it is to the chance concentration of a damaging type of inclusion.

Finally, it must be recognized that heat-affected zone toughness properties have not been exhaustively studied and that potential impairment may exist in other regions, or under other conditions of welding energy input. However, a rather comprehensive study reported by Peterson (Reference 8) showed that over a rather wide range of energy inputs, heat-affected zone toughness (as measured by Charpy impact specimens) remains essentially the same as unaffected parent plate. Compared to the weldmetal toughness problem, the heat-affected zone problem does not appear to be nearly as acute.

EFFECT OF CRACK DEPTH ON THE NET-FRACTURE STRESS
OF WELDMETAL DEPOSITED IN HEAT-B PLATE
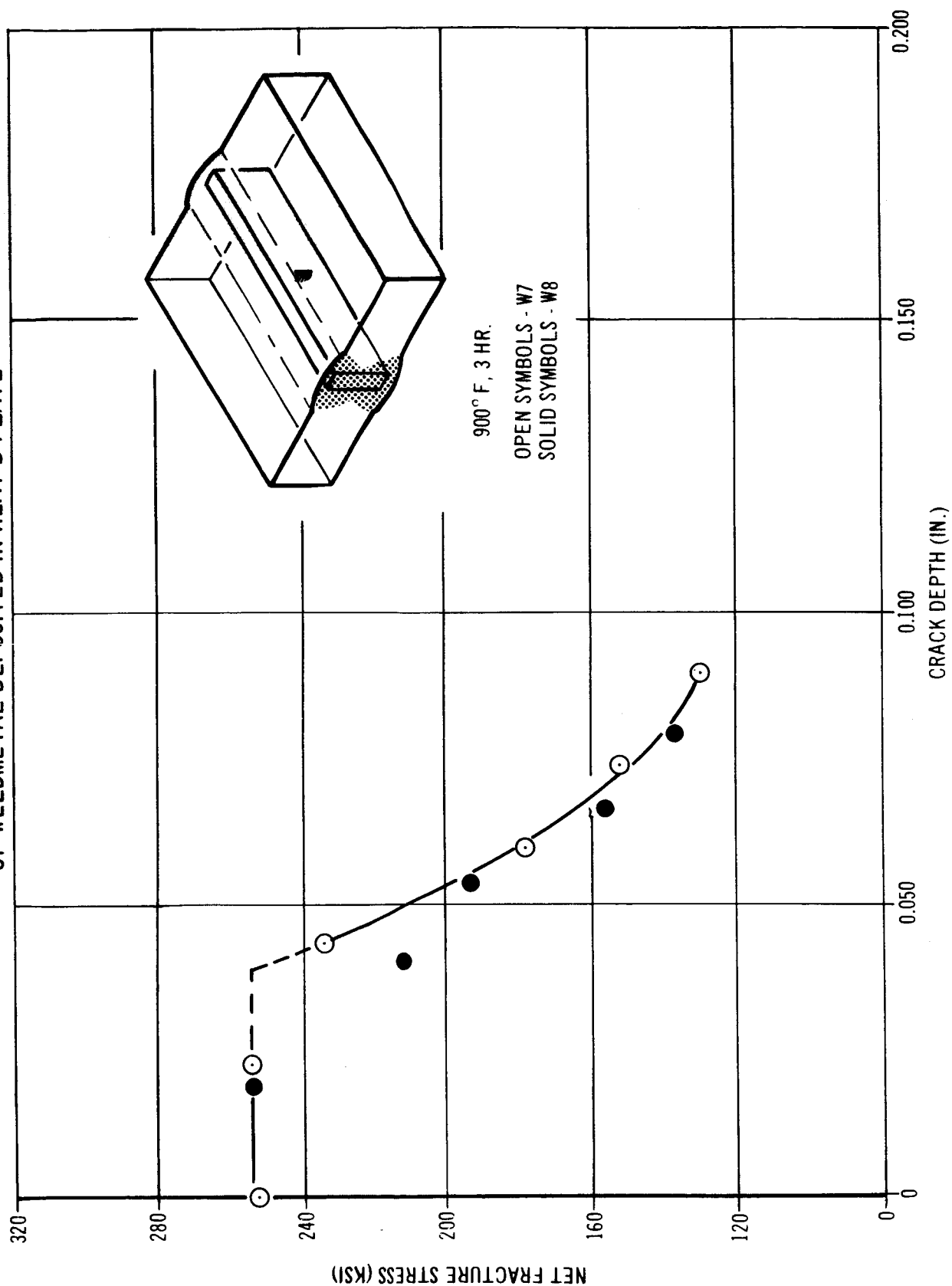
900° F , 3 HR.

OPEN SYMBOLS - W7
SOLID SYMBOLS - W8

NET FRACTURE STRESS (KSI)

CRACK DEPTH (IN.)

FIGURE 80

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EFFECT OF CRACK DEPTH ON NET FRACTURE STRESS
IN HEAT – AFFECTED ZONE REGIONS OF
WELDMENTS DEPOSITED IN HEAT – B PLATE

900° F, 3 HRS
TYPE W7 WELD

NUMBERS IN PARENTHESES
EQUAL K_{1C} $(KSI\sqrt{IN} \times 10^{-3})$
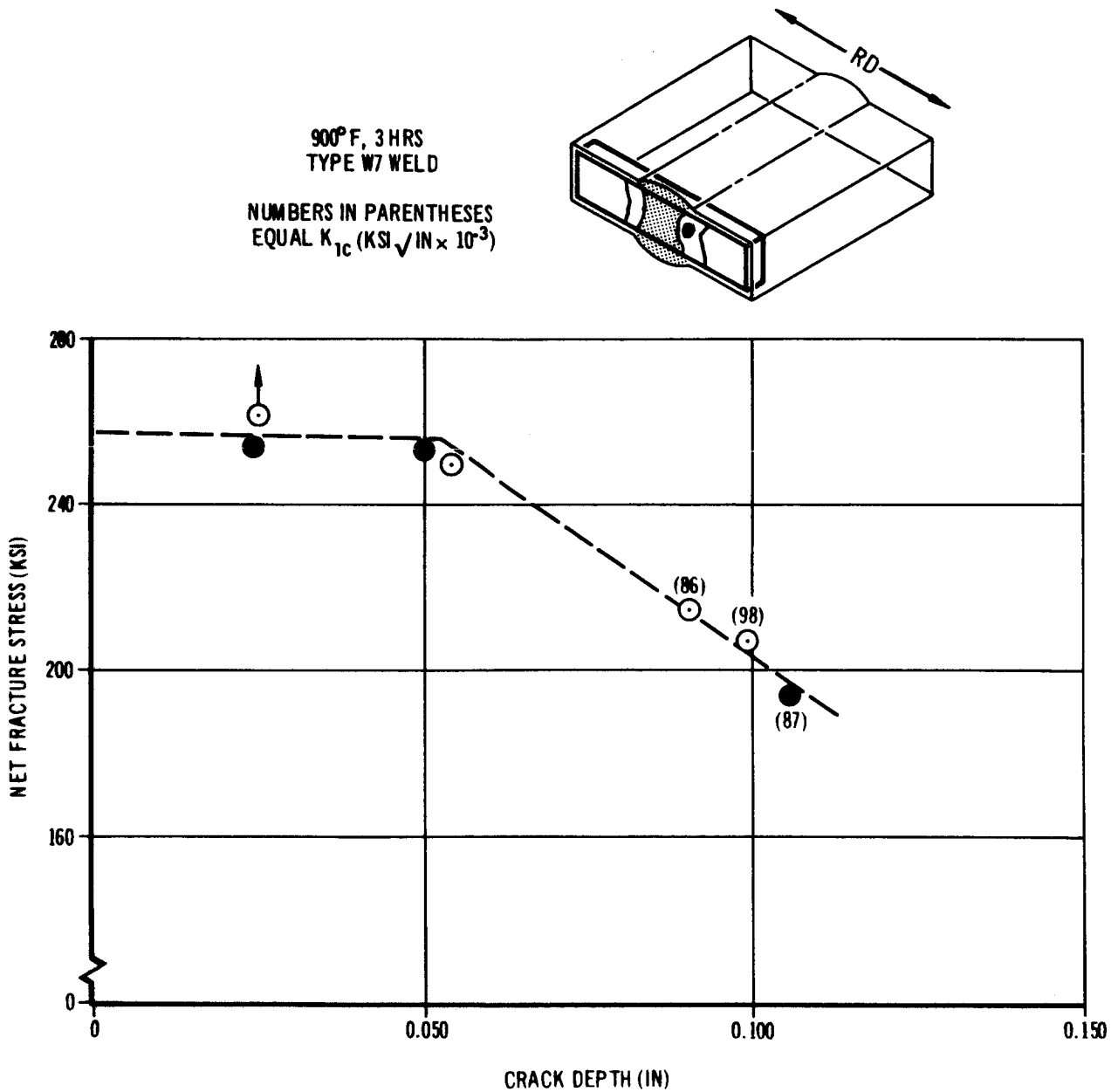
FIGURE 81

EFFECT OF CRACK DEPTH ON NET-FRACTURE STRESS
IN HEAT-AFFECTED ZONE REGIONS OF
WELDMENTS DEPOSITED IN HEAT-B PLATE

900°F, 3 HR
TYPE W7 WELD

AS-RECEIVED PLATE PLATE WELDS
● –CRACK PROPAGATION
PERPENDICULAR TO PLATE
ROLLING DIRECTION
▲ –CRACK PROPAGATION
PARALLEL TO PLATE
ROLLING DIRECTION

AGED PLATE WELDS
○ –CRACK PROPAGATION
PARALLEL TO PLATE
ROLLING DIRECTION

ARROWS DENOTE
FAILURES AWAY
FROM CRACK

NUMBERS IN PARENTHESES
EQUAL K_{Ic} (KSI $\sqrt{}$ IN. × 10-3)
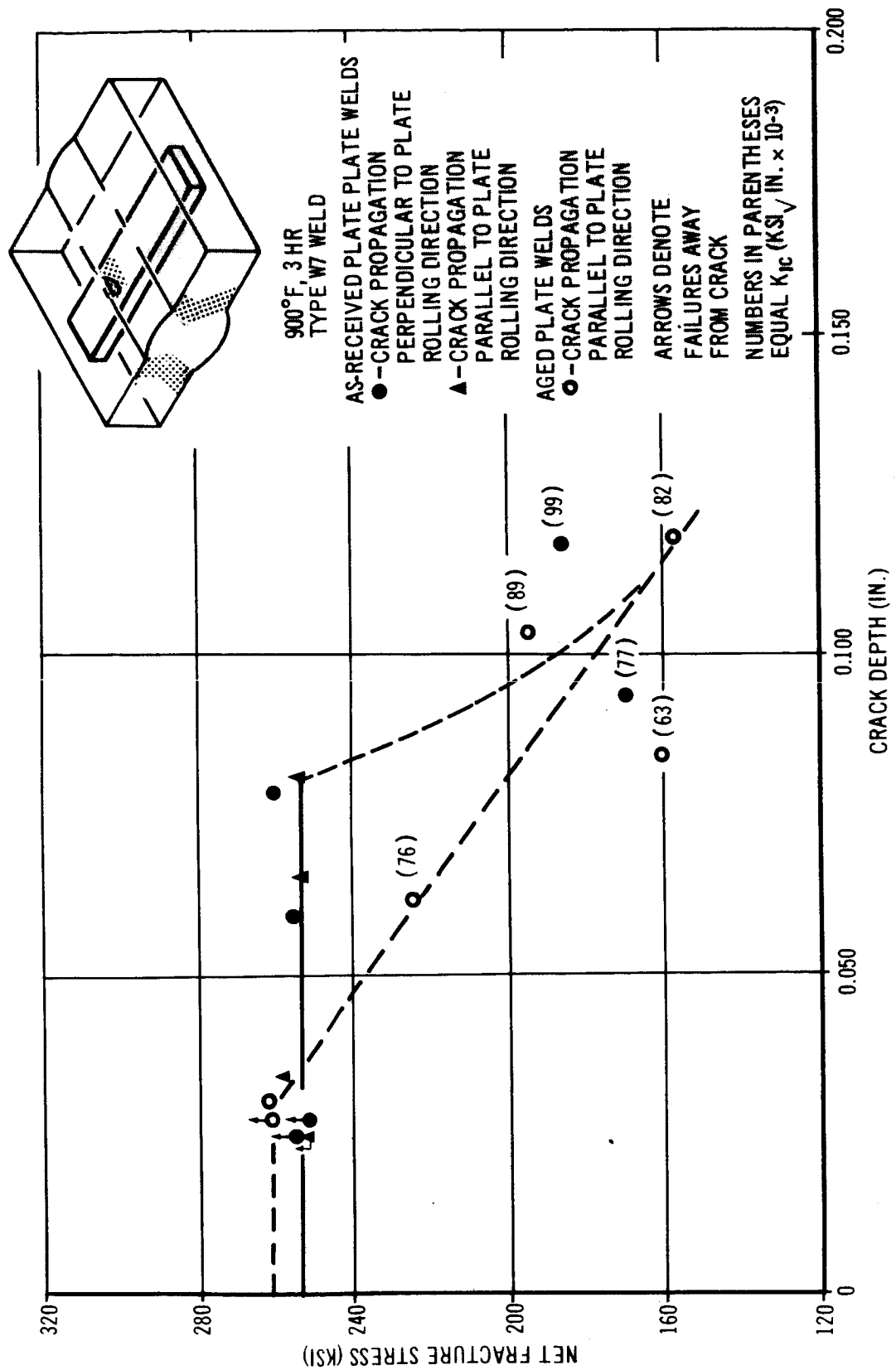
FIGURE 82

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4. CONTOURED PLATE WELDING

This section describes the results of an evaluation of production prototype welding under conditions simulating possible fabrication procedures for actual space launch vehicles. Weld repair procedures were also evaluated.

4.1 Preparation of Test Plates

Newport News Shipbuilding and Dry Dock Co. performed the fabrication tasks for evaluation. Four 10-ft x 2-ft x 3/4-in. thick sections from Heat B plate were formed (in the as-received condition) into 10-ft radius, contoured sections. The forming was accomplished using a 600 ton hydraulic bending press as illustrated in Figure 83. The forming was accomplished after the joint preparations had been machined. One set of two contoured sections was aged at 900°F for 3 hours. The other set was maintained in the as-received and formed condition.

Two contoured sections, of identical thermal history, were joined along their 10-ft lengths (which was perpendicular to the plate rolling direction). Welding was performed employing two experimental welding fixtures available at Newport News Shipbuilding and Dry Dock Co.

Figure 84 presents the joint design and welding conditions that were employed. The conditions are modified W8 conditions. Preliminary testing indicated the need for the enacted changes. The side I weld was deposited using the fixture shown in Figure 85. After side I

4.1   Preparation of Test Plate

was deposited the welded section was removed from the inside weld
fixture and clamped on the outside weld fixture as illustrated in
Figure 86. Manual carbon-arc gouging was employed to machine the
side 2 groove. Manual grinding with a rotary abrasive wheel was
employed to clean up the arc-gouged surfaces. The Side 2 weld was
then deposited.

Repair welds were simulated in both the aged and as-received welded
sections. This was accomplished by arc-gouging out a 5-ft length
from the side 1 weld and rewelding as shown in Figure 84.

During this welding operation a very practical problem plagued the
operation. During the flat plate welding (described in Section 3),
spatter was often encountered. Because of the comparatively short
weld lengths, no serious gas shielding problems resulted. However,
during the 10-ft weld substantial time was available for the
accumulation of spatter around the torch nozzle and on the under-
side of the trailing shield. Figure 87 illustrates typical accumula-
tion after a 10-ft long weld. Such accumulation severely impaired
gas shielding and very likely was the indirect cause of the lack-of-
fusion defects revealed by testing.

Following welding, the weldments were inspected radiographically.
Although occasional porosity was evident, the amount was within the
acceptable limit. No other defects were observed. The fact that no
other defects were radiographically detected is quite striking in
view of the prevalence of lack of fusion which was revealed on the
fracture surfaces of tested specimens.

144
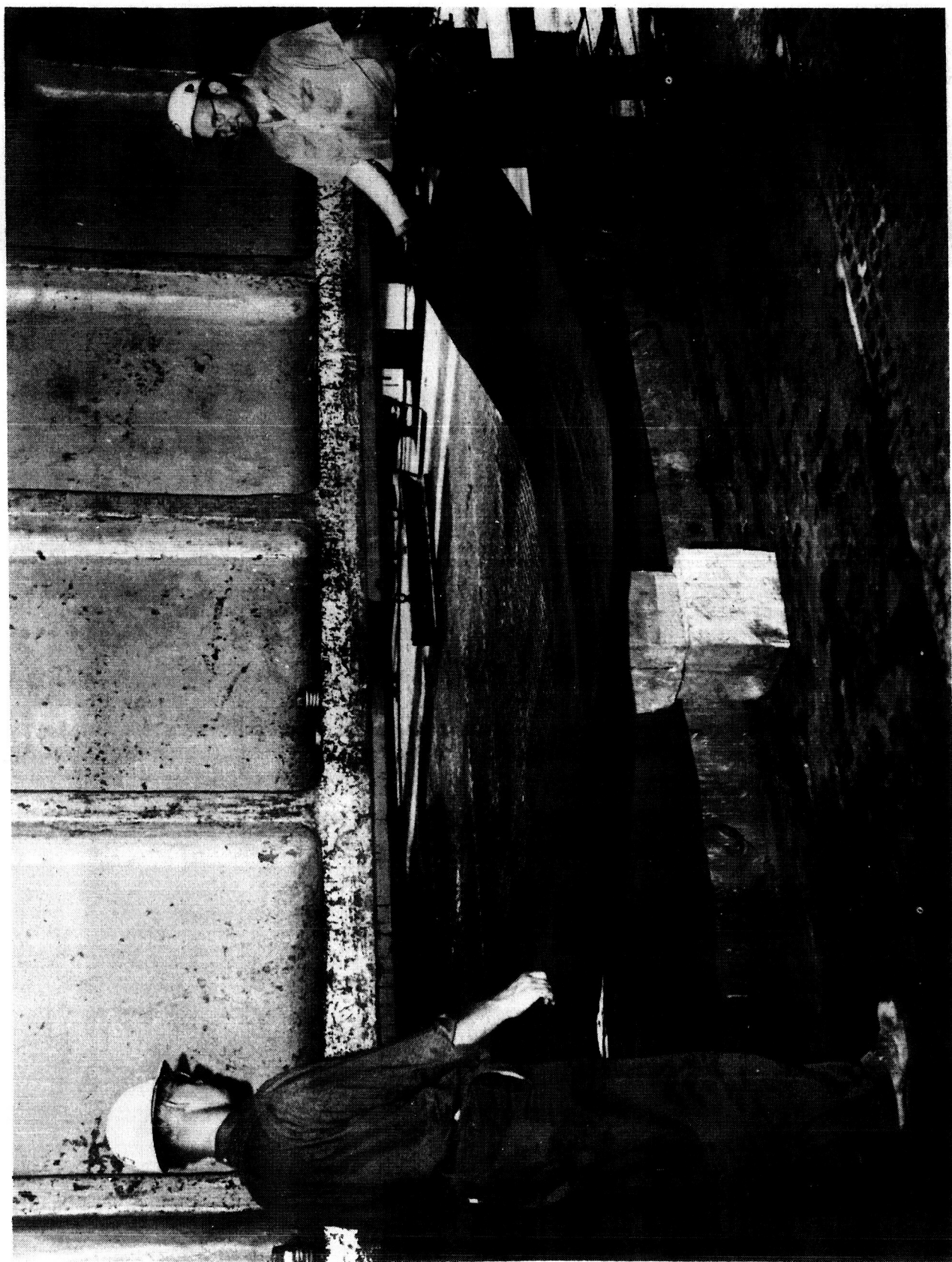
SETUP FOR FORMING OF TEN FOOT RADIUS CONTOURED SEGMENTS USING BENDING PRESS

FIGURE 83

JOINT CONFIGURATION AND WELDING CONDITIONS
FOR CONTOURED PLATE WELDS
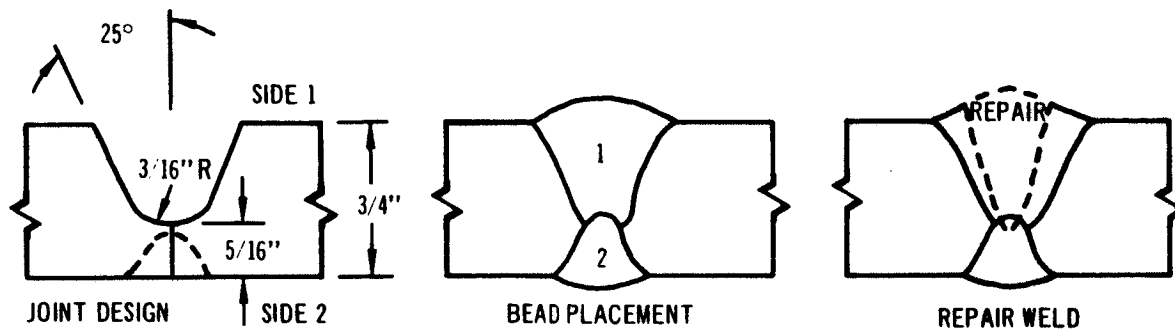
SIDE 1		SIDE 2		REPAIR WELD	
CURRENT	– 510 AMPERES	CURRENT	– 540 AMPERES	CURRENT	– 540 AMPERES
VOLTAGE 31.5	– 31.5 VOLTS	VOLTAGE	– 31.5 VOLTS	VOLTAGE	– 32 VOLTS
TRAVEL SPEED	– 6 ipm	TRAVEL SPEED	– 9 ipm	TRAVEL SPEED	– 9 ipm

PROCESS: MIG, DCRP
ELECTRODE; 0.093-IN. DIAMETER TYPE A1
TORCH GAS: 85 CFH ARGON
TRAIL SHIELD: 185 CFH ARGON
TORCH ANGLE: 3° FOREHAND

BASE PLATE – HEAT-B, 3/4"-IN THICK 18Ni-7Co-5Mo PLATE

FIGURE 84

146
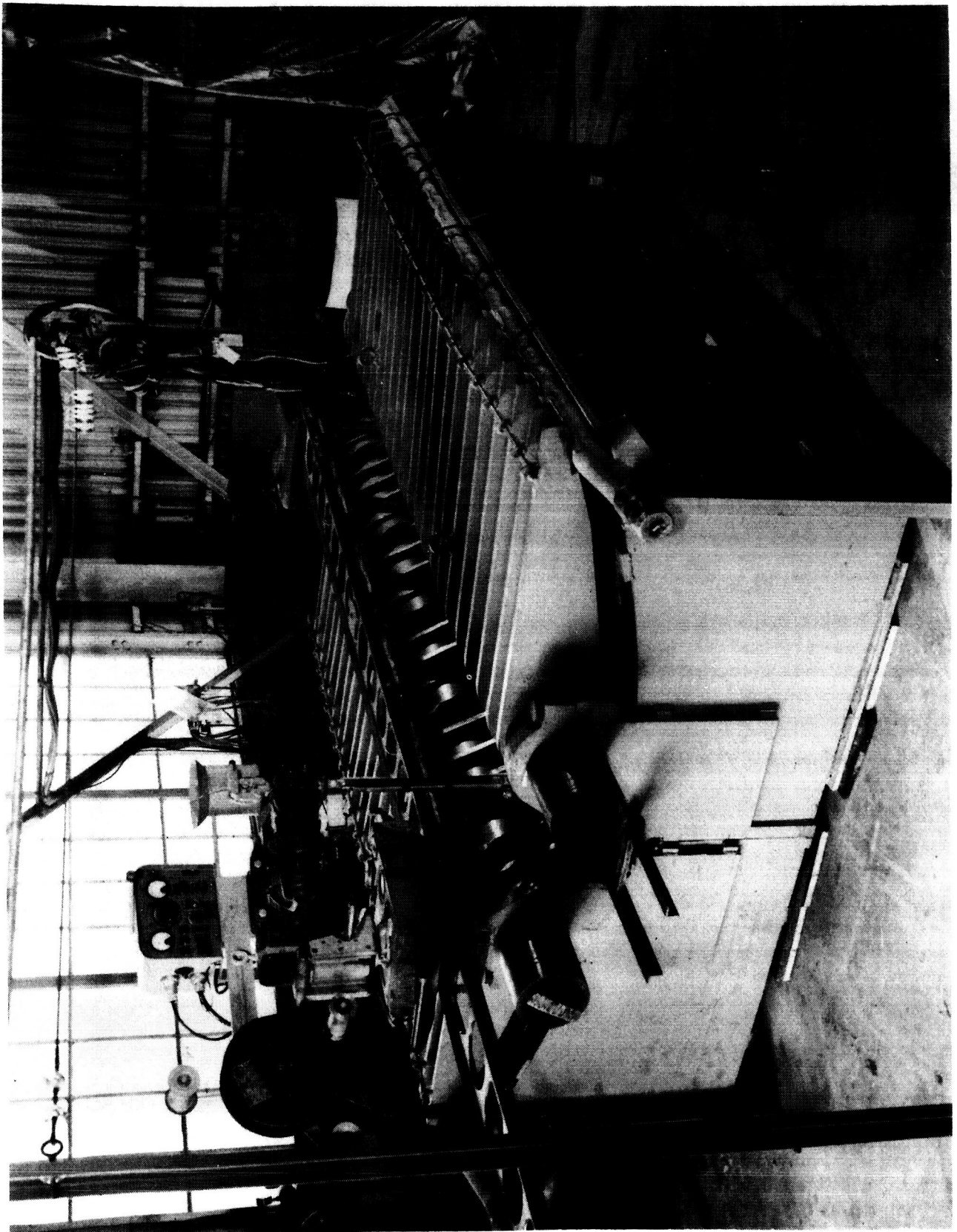
CONTOURED PLATE WELDING FIXTURE FOR INSIDE WELD

FIGURE 85

TYPICAL SPATTER ACCUMULATION ON THE UNDERSIDE OF THE TRAILING SHIELD AND ON TORCH NOZZLE AFTER THE COMPLETION OF ONE CONTOURED PLATE WELD

FIGURE 87

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4.2   Tensile Properties of Contoured Plate Welds

Tensile properties were evaluated using smooth 10" x 3/4" x 3/4" tensile specimens (Figure 49) oriented both transverse and parallel to the longitudinal axis of the weld. The specimens were aged at $900^\circ F$ for 3 hours. The longitudinal axis of symmetry of the longitudinal specimen coincided with the longitudinal axis of symmetry of the weld and consisted of approximately 80 per cent weld and 20 per cent plate heat-affected zone. For the transverse specimen, the longitudinal axis of the weld was coincident with the transverse axis of symmetry of the specimen.

The tensile results are presented in Table XV. Numerous nil-ductility failures occurred, and after several extensometer accidents, the measurement of yield strength was abandoned. Ultimate strength values ranged from 143,500 psi to 273,400 psi, and per cent elongations varying from zero to 5.5 per cent were obtained. Fifteen of the sixteen specimens failed through weldmetal. The fracture surfaces of these specimens exhibited two predominant types of flaws. Figure 88 illustrates a typical lack of fusion defect on the weldmetal fracture surface of a transverse specimen (222-D2). Figure 89 illustrates a typical porosity defect on a weldmetal fracture surface of a longitudinal specimen. The oblique crescent sections along two edges delineate plate heat-affected zone.

Lack of fusion appears to be a far more serious type defect than porosity. Several specimens exhibiting lack of fusion failed at very low stress levels. For example, specimen 222-D2 which is

4.2   <ins>Tensile Properties of Contoured Plate Welds</ins> (Cont'd.)

depicted in Figure 88 failed at 173,400 psi. When the failing

stress is calculated on the basis of net area, ultimate

stress is approximately 185,000 psi. Apparently the lack of fusion

defect affects mechanical behavior in a manner similar to that pro-

duced by a partial crack. No direct correlation with net fracture

stress data was possible, however, because of the irregular geometry

of the lack-of-fusion type defects.

The tensile data demonstrate that the weld quality was quite inferior

to that obtained for the W7 and W8 flat plate welds. Nonetheless,

the data also reveal that tensile properties equivalent to that

obtained in flat plate welds can be achieved.

4.3   <ins>Fracture Toughness Properties of Contoured Plate Welds</ins>

Fracture toughness properties of weld metal deposited in the contoured

plate sections were evaluated using the 8" x 11/16" x 5/16" PTC

specimen. The specimens were aged at 900°F for 3 hours. Because

of the lack of fusion type defects, secondary cracks often developed

away from the starter notch during flexural fatiguing. One specimen

failed during flexural fatiguing from a crack propagating through

an area of gross lack of fusion.

TABLE XV - TENSILE PROPERTY DATA FOR CONTOURED PLATE WELDS

10" × 3/4"× 3/4" SPECIMENS

SPEC. NO.	PLATE CONDITION PRIOR TO WELDING	SPEC. ORIENTATION	SPECIMEN TYPE	0.2% YIELD STRENGTH (KSI)	ULTIMATE STRENGTH (KSI)	% ELONG. (2-IN.)	LOCATION OF FAILURE & REMARKS
222-A1	As Rec'd.	L	As Deposited	-----	256.9	3.0	WM-LOF
222-A7	As Rec'd.	L	As Deposited	220.8	261.7	5.5	WM-LOF
222-B1	As Rec'd.	L	Repaired	-----	260.4	2.0	WM-P
222-B7	As Rec'd.	L	Repaired	-----	254.4	2.0	WM-P
222-A2	As Rec'd.	T	As Deposited	-----	143.5	0.0	WM-LOF
222-A8	As Rec'd.	T	As Deposited	-----	213.0	0.0	WM-LOF
222-B2	As Rec'd.	T	Repaired	-----	229.2	0.0	WM-LOF
222-B8	As Rec'd.	T	Repaired	249.3	249.3	0.2	WM-LOF
222-C1	Aged	L	As Deposited	239.6	266.4	1.4	WM-P
222-C7	Aged	L	As Deposited	-----	256.2	2.0	WM-P
222-D1	Aged	L	Repaired	260.9	273.4	2.0	WM-P
222-D7	Aged	L	Repaired	-----	251.6	5.5	WM-P
222-C2	Aged	T	As Deposited	-----	247.2	1.0	WM-LOF
222-C8	Aged	T	As Deposited	-----	245.1	1.5	WM-LOF
222-D2	Aged	T	Repaired	-----	173.4	0.0	WM-LOF
222-D8	Aged	T	Repaired	240.0	262.0	2.0	HAZ

NOTES:

1. Plates aged prior to welding were aged at 900°F for 3 hours.

2. All tensile specimens aged at 900°F for 3 hours.

3. L = Parallel to weld; T = transverse, across-the-joint.

4. WM-LOF - Weldmental, lack of fusion

5. WM-P - Weldmetal, porosity

6. HAZ - Heat-affected zone

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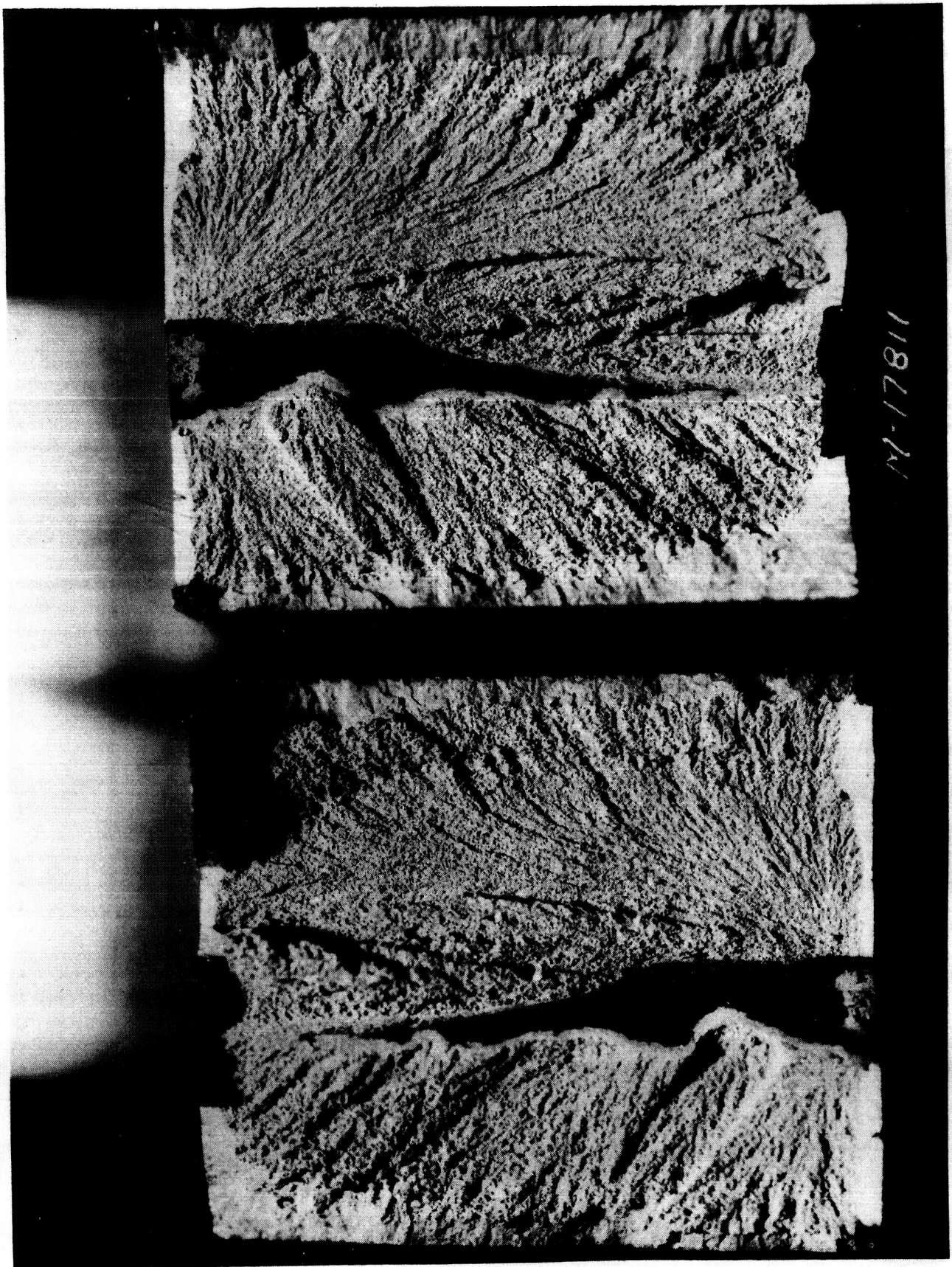
MAGN 6½X – TYPICAL LACK OF FUSION DEFECT IN CONTOURED PLATE TENSILE SPECIMENS

FIGURE 88

153
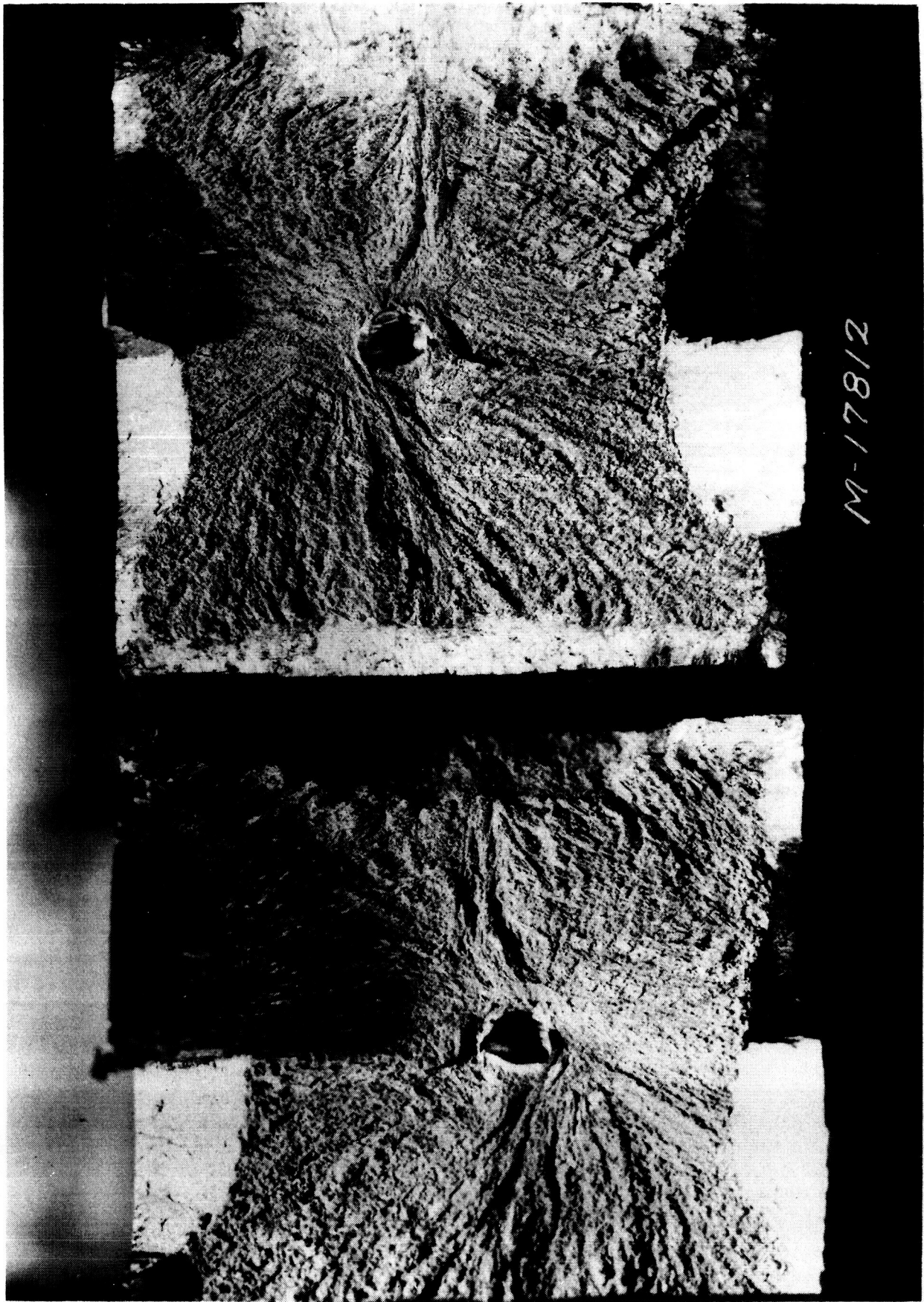
MAGN 6½X – TYPICAL POROSITY DEFECT IN CONTOURED PLATE TENSILE SPECIMENS

FIGURE 89

Table XVI presents the fracture toughness data on these specimens. More than half of the specimens developed secondary cracks during flexuring because of lack of fusion or porosity defects. As a result, crack propagation was often partially through weld and plate heat-affected zone. If such points are disregarded, the remainder of the data agrees reasonably well with the data generated on types W7 and W8 flat-plate welds. Figure 90 illustrates this comparison. Plane strain fracture toughness values, K_{IC}, also compare favorably with values for the flat plate welds (60-80 KSI $\sqrt{in.}$) subjected to the same post-weld aging treatment.

The data demonstrate the feasibility of transferring laboratory procedures into production procedures. However, significant practical problems must be overcome before such procedures could be performed with the necessary degree of confidence.

The results demonstrate that radiographic inspection may be totally inadequate for the detection of lack-of fusion defects in thick plate. Such defects may behave much like cracks and, therefore, they represent a very damaging type. More sensitive non-destructive inspection procedures should be explored for full scale space launch vehicle fabrication.

TABLE XVI - FRACTURE TOUGHNESS PROPERTY DATA FOR CONTOURED PLATE WELDS
8" x 11/16" x 5/16" SPECIMENS

Spec. No.	Plate Condition Prior to Welding	Spec. Orientation	Specimen Type	Crack Length (in.)	Crack Depth (in.)	Gross Fracture Stress (KSI)	Net Fracture Stress (KSI)	Applicable 0.2% Yield Stress (KSI)	Gross K_{IC} (KSI $\sqrt{in}$)	Net K_{IC} (KSI $\sqrt{in}$)
222A3	As Rec'd.	T	As Deposited	0.123	0.057	245.6	252.0	---	**	**
222A4	As Rec'd.	T	As Deposited	0.112	0.050	198.3	202.5	246.6	59.6	61.1
222A5	As Rec'd.	L	As Deposited	0.080	0.038	234.5	237.4	246.6	60.4	61.2
222A6	As Rec'd.	T	As Deposited	Failed During Flexure Fatigue						
222B3	As Rec'd.	T	Repaired	*	---	250.0	250.0	---	---	---
222B4	As Rec'd.	T	Repaired	0.112	0.050	233.7	238.9	246.6	71.2	73.0
222B5	As Rec'd.	L	Repaired	0.069	0.025	231.3	232.0	246.6	54.8	55.1
222B6	As Rec'd.	T	Repaired	0.390	0.147	81.1	103.3	---	**	**
222C3	Aged	T	As Deposited	0.264	0.117	163.6	184.8	---	**	**
222C4	Aged	T	As Deposited	0.230	0.125	133.0	149.5	---	**	**
222C5	Aged	T	As Deposited	0.155	0.098	206.8	219.2	---	**	**
222C6	Aged	L	As Deposited	0.080	0.038	244.4	247.2	246.6	63.2	64.0
222D3	Aged	T	Repaired	0.112	0.085	211.6	215.5	---	**	**
222D4	Aged	T	Repaired	0.188	0.075	187.2	198.5	246.6	72.4	77.1
222D5	Aged	L	Repaired	0.076	0.031	228.2	230.0	246.6	57.0	57.5
222D6	Aged	L	Repaired	0.179	0.060	176.3	185.0	246.6	64.9	68.4

NOTES:

1. All specimens aged 900°F, 3 hours.

2. * Broke away from crack

3. ** Secondary cracks developed because of lack of fusion defects and crack propagation surface was composed of both weldmetal and heat-affected zone material in various proportions.

4. Gross Fracture Stress = Failing load divided by gage area

5. Net Fracture Stress = Failing load divided by gage area minus crack area.

DEPENDENCE OF NET FRACTURE STRESS
ON CRACK DEPTH FOR CONTOURED PLATE
WELDMETAL AGED AT 900°F FOR 3 HOURS

CONTOURED PLATE WELDS

⊙ AS DEPOSITED & AGED

● REPAIRED & AGED

NUMBERS IN PARENTHESES
EQUALS K_{Ic} (KSI $\sqrt{}$ IN. × 10⁻³)

FLATE PLATE
W7 & W8 WELDMETAL
(900°F, 3 HRS)

⊙(64)
⊙(61)
●(73)
●(55)
●(57)
⊙(60)
●(68)

NET FRACTURE STRESS (KSI)

280
240
200
160
120
0

CRACK DEPTH (IN)

0   0.050   0.100   0.150   0.200

FIGURE 90

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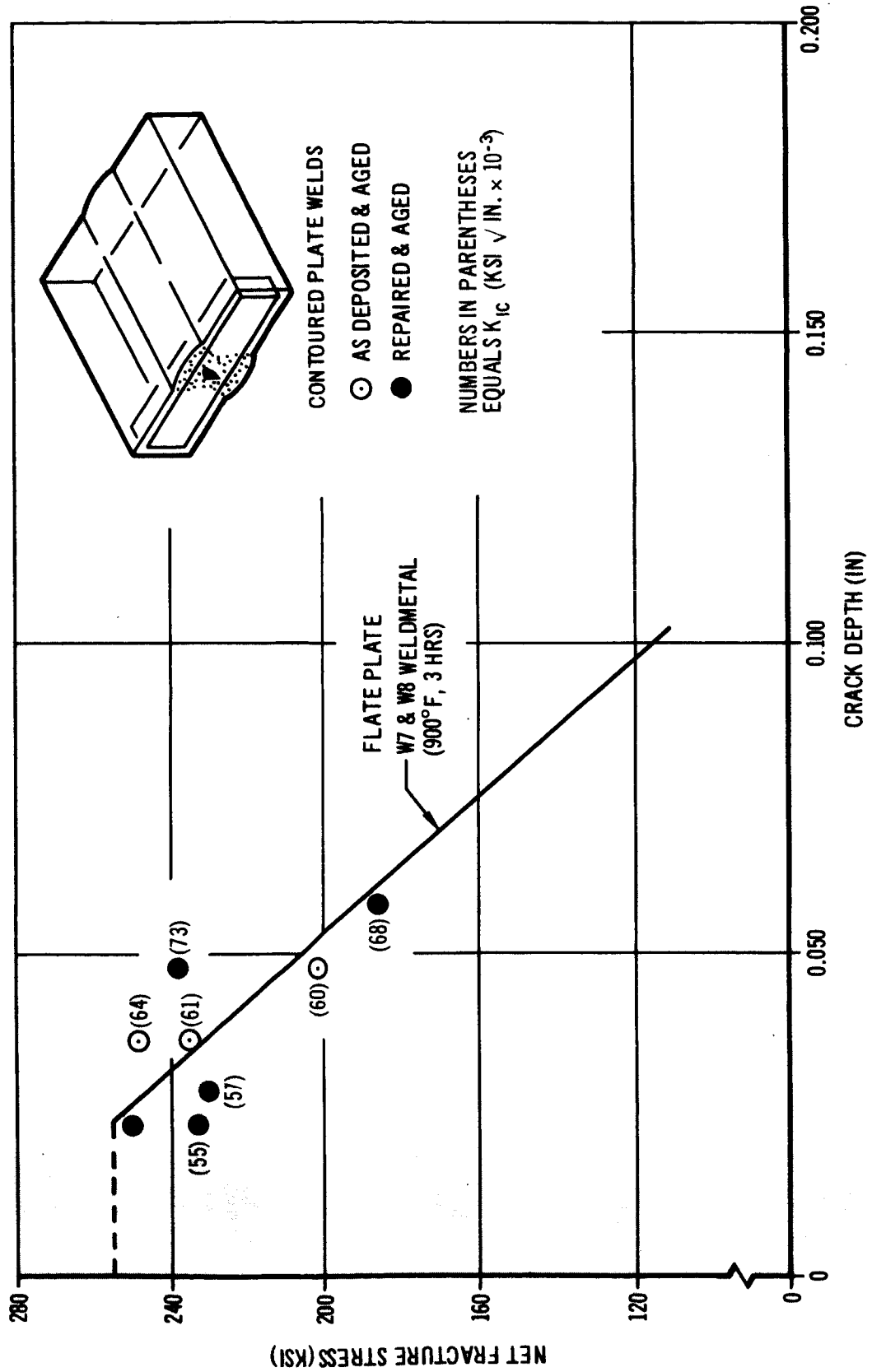
5.   EFFECT OF ENVIRONMENT ON THE SUSTAINED LOAD BEHAVIOR OF PLATE AND WELDS

The reliability and performance of any pressure vessel fabricated from 18Ni-7Co-5Mo alloy steel will be significantly affected by the slow growth of cracks under sustained static loads. Previous studies performed at Douglas (Reference 12) demonstrated that cracks introduced in high strength AISI 4340 steel sheet resisted slow growth under sustained loads, equal to 98% of ultimate, when tested in air. However, the addition of moisture resulted in the rapid growth of cracks and catastrophic failure at low stress levels.

Short time sustained load conditions, under potentially damaging environmental conditions prevail when a pressure vessel is being tested. Present industry practice is to proof test steel pressure vessels with oil so as to avoid the possibility of failure induced by accelerated crack growth (of cracks or crack-like flaws that escaped detection during inspection).

This section presents data pertaining to the sustained load behavior of 18Ni-7Co-5Mo plate and welds. Caution in the selection of a proof testing media and the need for possible control of surface condition is indicated. Furthermore, weld behavior is inferior to plate and may require special attention.

5.1   Sustained Load Testing Procedure

Both plate and weldments were tested employing the 24-in PTC specimens, (Figure 8, Section 2.4) and the 8-in PTC specimen (Figure 9, Section 2.4). The thickness type 8-in PTC specimen

5.1   Sustained Load Testing Procedure (Cont'd.)

Figure 35, Section 2.9.2) was used. In the case of plate, the specimens were transverse to the rolling direction. Weld evaluations were performed using Type W7 welds (Table XI, Section 3.2) employing the specimen and crack orientations illustrated in Figure 66 (Section 3.8). Most of the specimens were aged at 900°F for 12 hours although a few were also aged for 3 hours. The 12 hours age was selected for the majority of the testing since such a treatment had previously been observed to produce toughness degredation. Therefore, the results might represent a potentially extreme condition.

All the specimens were tested containing partial thickness cracks. It was originally intended that all the cracks be approximately equal in size to that determined to be critical in the fracture toughness testing. Cracks of critical size were selected since failure would be expected to occur at tensile ultimate strength unless crack growth occurred. Any crack growth would thereby extend the crack beyond critical size and induce a lower strength failure. However, several exceptions prevailed because of spurious cracking in specimens.

Duplicate specimens were tested in each of four environments: a) ambient air ranging in relative humidity from 21 to 65 percent at dry bulb temperatures from 70 to 78°F, b) type "Texaco 519" corvus oil, c) NaCl solution 20%, by weight, prepared with deionized water ranging in P^H from 5.9 to 7.8 and having a specific electrical conductivity of 178 ohm^{-1},- cm^{-1} and d) distilled, deionized

5.1   Sustained Load Testing Procedure (Cont'd.)

water ranging in p^H from 5.7 to 7.8 and specific electrical conductivity ranging from 0.001 to 0.002. The liquid testing environments were contained in plastic envelopes taped on the specimen. Approximately constant liquid volumes were used (about 30 c.c. for the 8-in PTC specimens and about 120 c.c. for the 24-in PTC specimens). Liquid contacted the specimen surfaces over a distance extending approximately 1-1/2 inches on either side of the crack. This extent of contact was deliberately selected so that liquid would come in full contact with heat-affected zone and weldmetal regions in the weld specimens.

The specimens were step-loaded in three intermediate steps of one hour duration each, unless failure occured. A final step-load to failure was performed if the specimen survived the first three hours. The step loads were 90, 95, 97 per cent of estimated ultimate strength (based on previous data). Loads were maintained to within 1/2% of nominal.

Test results are described in the following two sections. Data are summarized in Table XVII.

5.2   Sustained Load Behavior of Plate

The tests performed on the four 24-in PTC specimens were conducted employing plate covered with the original crazed mill scale. Previous fracture toughness tests were performed after the mill scale had been removed by grinding. As it turned out, the crazed mill

TABLE XVII

EFFECT OF VARIOUS ENVIRONMENTS ON NET FRACTURE STRENGTH OF PLATE AND W7 TYPE WELDMENTS UNDER SUSTAINED LOAD

Spec. No.	Aging Time at (900°F) (Hours)	Crack Length (Inches)	Crack Depth (Inches)	Environment	ESTIMATED SUSTAINED STRESS (KSI) % of ULTIMATE 90	95	97	100	Actual Sustained Stress (KSI)	Time To Failure (Min)	Location of Failure if Not Through Specified Cracks
24" x 3" x 3/4" Parent Plate											
P-54	3	0.085	0.040	20% NaCl	259	274	279	288	285	180+	
		0.110	0.045								
P56	12	0.100	0.046	20% NaCl	266				279	60+	
31W5	3	0.100	0.045	20% NaCl	259				272	60+	
31W8	12	0.100* (Plus Numerous Spurious Cracks)	0.045	20% NaCl					237	0	Failed through several spurious cracks
24" x 3" x 3/4" Weldments W7 Type											
6W5	3	0.058	0.024	20% NaCl	235	247	250	260	250	121	Failed away from crack through apparent weld flaw.
6W6	12	0.058*	0.024	20% NaCl	235	247	250	260	247	68	
8" x 11/16" x 5/16" Parent Plate											
PP5	12	0.091	0.045	Air	260	274	280	289	294	180+	
PP12	12	0.091	0.043	Air	260	274	280	289	289	180+	
PP6	12	0.060*	0.030	20% NaCl	260	274	280	289	290	180+	
PP11	12	0.060*	0.030	20% NaCl	260	274			274	95	Failed away from crack
PP7	12	0.060*	0.030	H$_2$O	260	274	280	289	288	180+	Failed away from crack
PP10	12	0.060*	0.030	H$_2$O	260	274	280	289	288	180+	Failed away from crack
PP8	12	0.060*	0.030	Oil	260	274	280	289	292	180+	Failed away from crack
PP9	12	0.060*	0.030	Oil	260	274	280	289	292	180+	Failed away from crack
8" x 11/16" x 5/16" Weldments W7 Type											
2B1	12	0.060*	0.030	Air	232	245	250	258	250	168	Failed away from crack (HAZ)
4E1	12	0.062	0.031	Air	232	245	250	258	230	0	Failed away from crack (eyebrow region)
2B2	12	0.060*	0.030	20% NaCl	232	245			245	93	
4E2	12	0.061	0.033	20% NaCl	232				232	43	
2B3	12	0.060*	0.030	H$_2$O	232	245	250	258	245	155	Failed away from crack (HAZ)
4E3	12	0.075	0.035	H$_2$O					228	0	
2B4	12	0.060*	0.030	Oil	232	245			245	103	Failed away from crack (eyebrow region)
4E4	12	0.120	0.060	Oil					209	0	Failed through spurious crack

NOTES:

1. * Crack depth estimated on the basis of original crack length (See Figure 37)
2. Zero time in time to failure column denotes failure during initial loading
3. 180+ in time to failure column denotes failure immediately after the one hour, 97% stress condition, and following the final step load to failure.
4. 60+ in time to failure column denotes failure immediately after the one hour, 90% stress condition, during the second step load to 95%.

5. 2   <u>Sustained Load Behavior of Plate</u> (Cont'd.)

scale acted as an initiator for multiple cracks during flexural
fatigue. The prevalence of multiple cracks makes some data interpret-
ation somewhat difficult.

The four 24-in. transverse plate specimens were tested in 20% NaCl
(Table XVII). Specimens were aged at $900^{o}F$ for 3 and 12 hours,
respectively. Only one of the four specimens sustained the full 3
hour test period. This specimen exhibited two separate cracks on the
fracture surface. One specimen exhibiting multiple cracks failed
upon initial loading. Two specimens, which did not exhibit spurious
cracks, failed after 60 minutes upon being loaded from the 90 to 95%
level.

The 8-in PTC plate specimens, which were fully machined on all sur-
faces, exhibited generally different behavior than that exhibited by
the 24-in PTC specimens. Figure 91 portrays the results for the
tests performed in the four different environments on plate and
welds (welds will be discussed later). As may be seen, seven of
the eight plate specimens survived the full 180 minute test duration,
failing at the 100% level. The single early failure occured in the
20% NaCl solution after a 35 minute exposure at the 95% level.
Post-failure examination revealed that the specimen failed near a
grip end probably through a stress riser induced by the grips.

Comparison of the behavior of the 24 and 8-in specimens tested in
the four environments is illustrated in Figure 92. The data indicate
that the condition of the exposed surface (mill scale versus machined)

5.2   Sustained Load Behavior of Plate (Cont'd.)

may be an important factor, and that 18Ni-7Co-5Mo plate is capable

of exhibiting rather remarkable resistance to slow crack growth in

environments that are rather hostile to high-strength, low-alloy

steels (e.g., AISI 4340).

5.3   Sustained Load Behavior of Welds

The data presented in Figures 91 and 92 show that the welds were

substantially inferior to the plate. Not one of the two 24-in and

eight 8-in PTC specimens survived the full 180 minute test duration.

Three 8-in specimens failed during loading; however, one of these

(tested in corvus oil) had an excessively large crack which accounts

for the relatively low strength failure. Interestingly, all three of

these initial-loading failures occured in the 4E weld series (see

Table XVIII). The remaining 4E specimen that was tested failed after

43 minutes at the 90% level. Four specimens tested from the 4B

series all failed before completing 180 minutes exposures: however,

their lives were much longer than those exhibited by the 4E specimens.

Furthermore, while all of the 4E specimens failed through partial

thickness cracks, none of the 4B series did so. Failures of all of

the 4B specimens, suprisingly, were located in heat-affected zones,

and no cracks were apparent on the fracture surfaces. No explanation

for the differences in behavior is evident. Additional study of

weldment behavior appears to be necessary.

EFFECT OF ENVIRONMENT ON NET FRACTURE STRESS OF PLATE
AND TYPE W7 WELDMENTS UNDER SUSTAINED LOAD
(AGED AT 900°F, 12 HOURS)

FIGURE 91

164
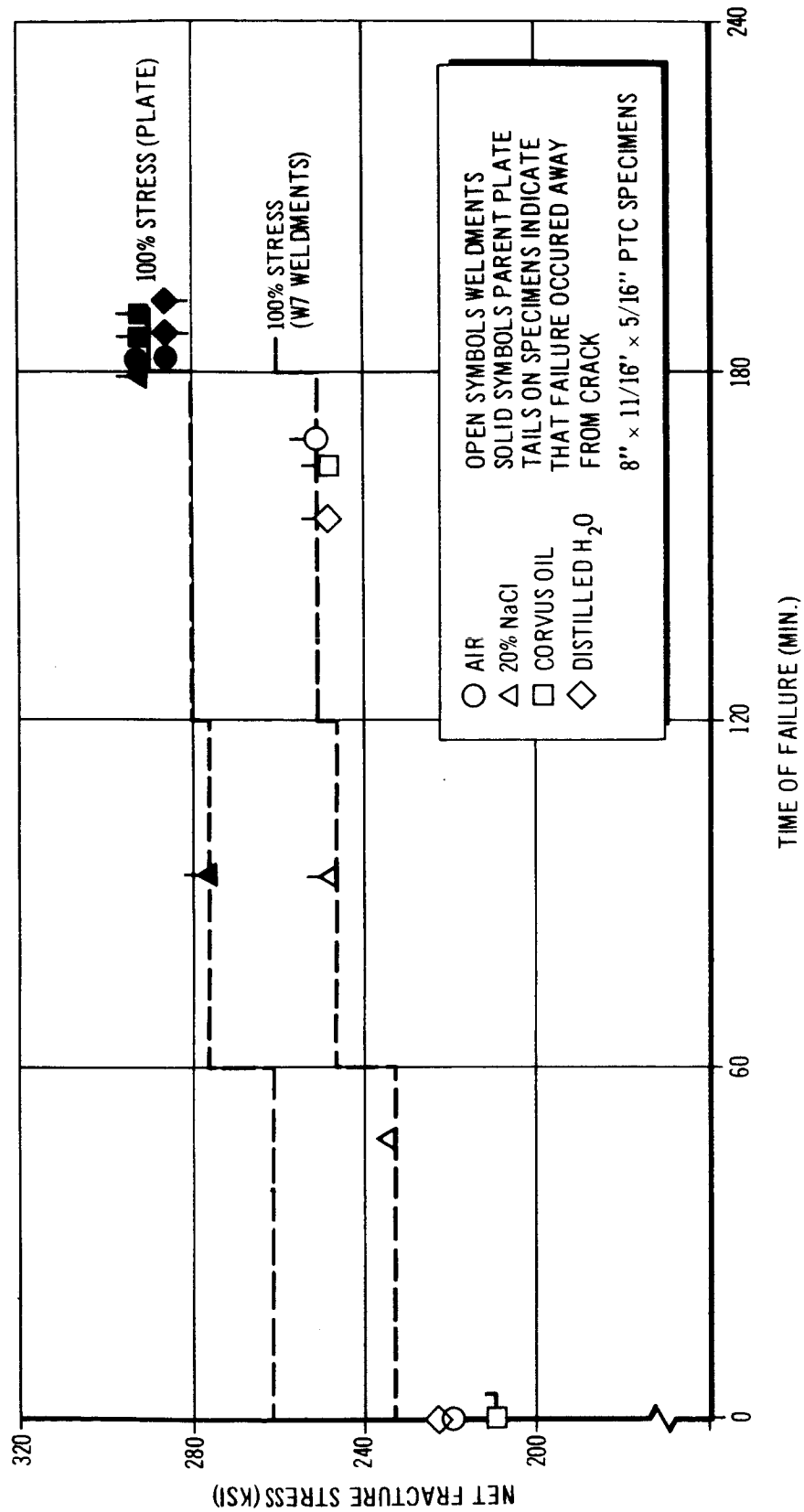
HISTOGRAM ILLUSTRATING FREQUENCY OF
FAILURE IN VARIOUS TIME RANGES FOR
SPECIMENS SUBJECTED TO SUSTAINED LOADS

AGED AT 900°F, 12 HOURS
(3 AT TOP OF COLUMN INDICATE 3 HOURS)

PLATE
WELDMENTS
8" × 11/16" × 5/16" PTC
24" × 3" × 3/4" PTC

PER CENT OF CALCULATED NET FAILURE STRESS

FAILURE TIME RANGE

LOADING
(ZERO TIME)

FAILURE WITHIN
59 MIN.

FAILURE WITHIN
59 TO 119 MIN.

FAILURE WITHIN
120 TO 180 MIN.

LOADED TO FAILURE
AFTER 180 MIN.
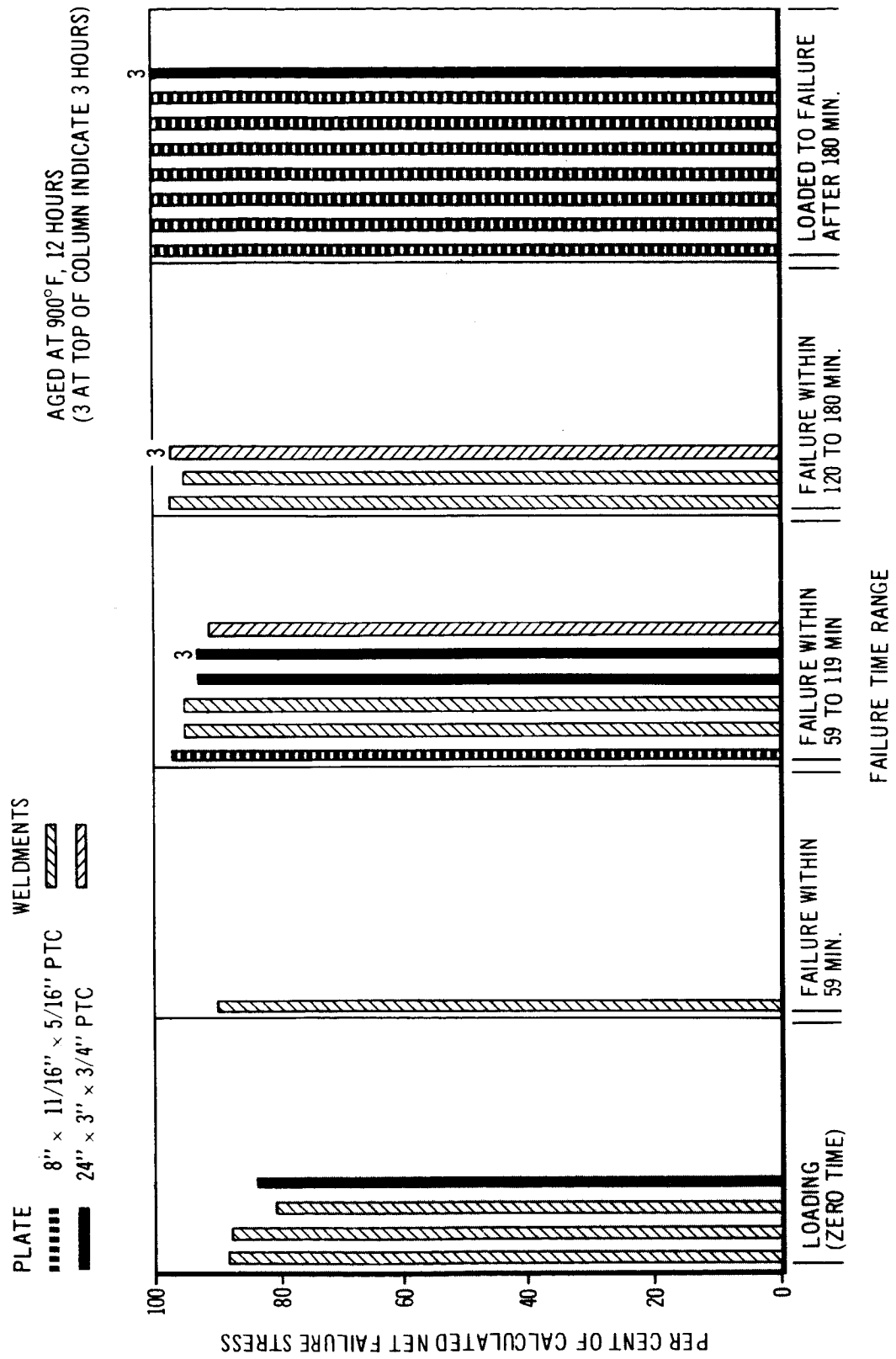
FIGURE 92

6.   <u>METALLOGRAPHIC OBSERVATIONS MADE BY OPTICAL AND ELECTRON MICROSCOPY</u>
          <u>AND ELECTRON FRACTOGRAPHY</u>

          The physical metallurgy and phase relationships of maraging alloys

          have been described in several publications (References 9-11, 13),

          but there remains much uncertainty concerning the exact strengthening

          mechanisms. No attempt will be made here to depict the numerous

          microstructural changes that are produced by thermal treatment.

          This section instead presents a brief summary of a very intensive

          metallographic analysis which has been undertaken in fulfilment of

          this contract and as part of previous Douglas sponsored work.

          Particular emphasis is placed on metallurgical factors related to

          weldmetal fracture toughness, since this represents the principal

          mechanical property deficiency of maraging steel welds. The

          observation of a phase, which is identified in a later section as

          titanium nitride, is presented. Electron fractography has revealed

          this phase as a predominant feature on the fracture surfaces of

          weldmetal.

          The metallographic evidence serves to support the hypothesis that

          titanium nitrides, either directly or indirectly, are responsible

          for the inferior fracture toughness of maraging steel weldmetal.

6.1   <u>Parent Plate and Heat-Affected Zone Microstructure</u>

          Figures 15 and 16 (section 2.7.2) illustrates typical optical

          micrograph of 3/4" thick, 250 KSI grade, 18Ni-7Co-5Mo maraging plate.

          The banded structure illustrated is quite common and varies consider-

          ably in severity from heat-to-heat, and to some extent from region-

(Cont'd.)

to region within a given plate. The sharp-cornered inclusions are common constituents in the banded zones. These types of inclusions are often observed to be gold colored. Table VII (Sec. 2.7.2) presented inclusion ratings for specimens taken from Heats I, A, and B plate. Angular inclusions of the type illustrated in Figures 15 and 16 represent the most conspicuous type present. These types of inclusions have been identified as titanium nitride or carbonitride in titanium bearing steels (References 14,15).

Figure 93 illustrates the appearance of angular inclusions on the rapid progagation fracture surface of a parent-plate plane-strain fracture toughness specimen. The matrix surrounding the inclusion consists of aged martensite. This fractograph was obtained using electron-fractographic techniques on an etched fracture surface employing a two-stage plastic-carbon replication technique. The inclusion appears to be fragmented as evidenced by replica seepage, and evidently fractured by clevage mode. These types of inclusions were by no means heavily concentrated on such parent plate fracture surfaces, but were sufficiently common to be frequently encountered. Significantly, the surface immediately surrounding this type of inclusion is quite flat indicative of a low-ductility rupture (References 16, 17) or a highly localized state of triaxial stress. Figure 94 illustrates the more typical dimpled structure of rapid propagation regions in parent plate. This type of fracture surface structure is characteristic of ductile rupture (References 16, 17). The fractograph also illustrates, in the upper right-hand corner, a

ANGULAR INCLUSIONS OBSERVED ON THE FRACTURE SURFACE OF 3/4 INCH THICK 18Ni-7Co-5Mo PLATE
ETCHED SURFACE-2 STAGE PLASTIC CARBON REPLICA-45° CHROMIUM SHADOWED
ETCHANT-MIXED ACIDS PLUS CUPRIC CHLORIDE
MAG: 13,670 X

FIGURE 93

TYPICAL DIMPLED STRUCTURE
ON THE FRACTURE SURFACE OF
3/4 INCH THICK 18Ni-7Co-5Mo MARAGING STEEL PLATE
UNETCHED SURFACE - 2 STAGE PLASTIC-CARBON REPLICA
45° CHROMIUM SHADOWED
MAG: 6,5000X

FIGURE 94

UNUSUALLY HIGH CONCENTRATION OF
ANGULAR INCLUSIONS ON THE RAPID PROPAGATION
FRACTURE SURFACE THROUGH A HEAT AFFECTED ZONE REGION
ETCHED SURFACE - 2 STAGE PLASTIC CARBON REPLICA
45° CHROMIUM SHADOWED
ETCHANT - CARAPELLAS REAGENT
MAG: 6,500 X

FIGURE 95

<u>Parent Plate and Heat-Affected Zone Microstructure</u> (Cont'd.)

region containing angular inclusions of the type illustrated in

Figure 93. The flat, non-dimpled surface in the vicinity of the

inclusions is apparent.

Figure 95 illustrates a fractograph of a rapid propagation fracture

surface through a heat-affected zone region. A rather high con-

centration of angular inclusions is observed, which is quite typical

for this particular specimen. Rather low plane-strain fracture

toughness (K_{IC} = 63 KSI $\sqrt{in}$, see Section 3.10) also characterized

this specimen. The relatively flat features of the fracture are

evident. In general, heat-affected zone fracture surfaces through

eyebrow regions were predominately dimpled and similar to that

illustrated in Figure 94.

In summation, metallographic observations reveal that angular non-

metallic inclusions, resembling titanium nitride, are prevalent in

18Ni-7Co-5Mo maraging steel plate. Fractographic analysis indicates

that these angular inclusions tend to promote relatively flat

fracture surfaces, and that the inclusions themselves fracture by

apparent clevage mode. Fractographic analyses thus far conducted

have revealed that low fracture toughness is associated with an

abundance of these inclusions on the fracture surface. These

observations demonstrate the potential damaging influence of such

inclusions in plate or heat-affected zone regions.

6.2   <u>Weldmetal Microstructure</u>

Figure 96 illustrates the typical microstructure prevalent in aged
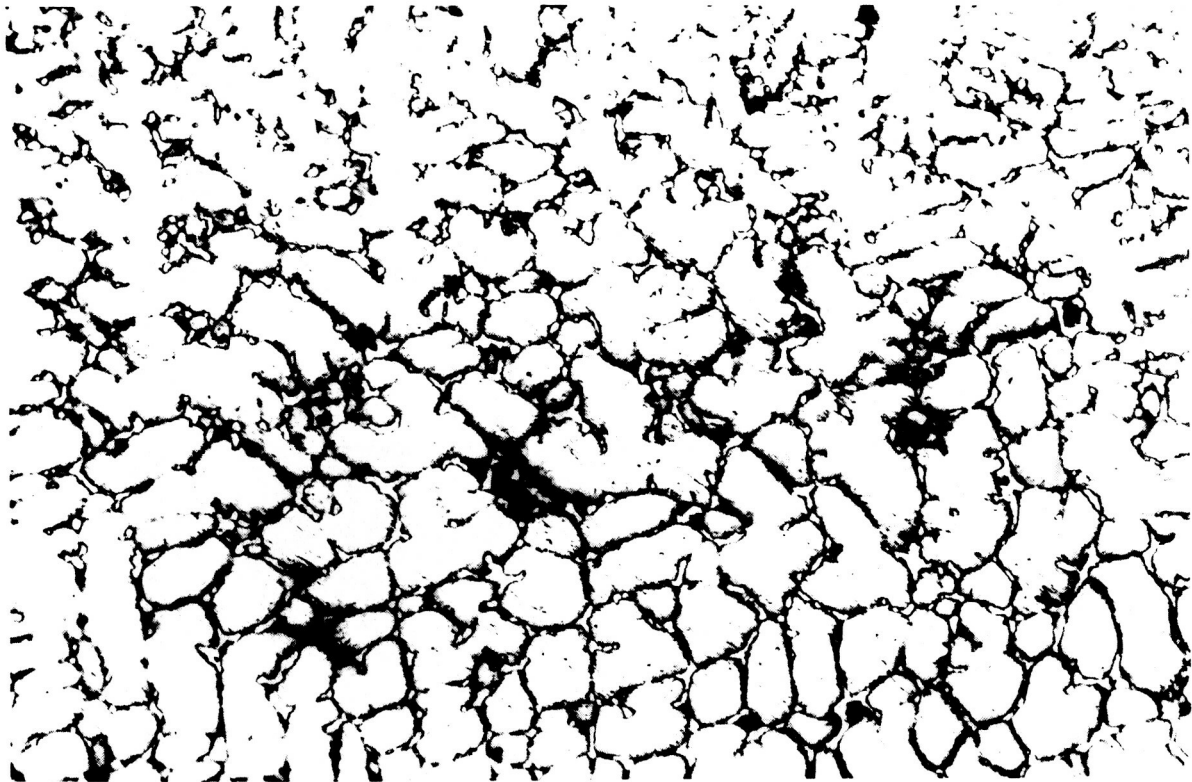
TYPICAL AGED WELDMETAL MICROSTRUCTURE
ETCHED - MIXED ACIDS PLUS CUPRIC CHLORIDE
MAG: 250X

FIGURE 96

maraging steel weldmetal. Light-etching islands form cell boundaries throughout an aged martensitic matrix. The light etching islands are believed to be reverted austenite enriched with austenite-stabilizing elements such as carbon, nickel, and nitrogen. Alloy segregation, which promotes the localized reversion to austenite in weldmetal, probably occurs during the non-equilibrium solidification and cooling of the weld deposit. Optical microscopy cannot reveal the fine details of structure which exist in such regions; however, electron microscopy is well suited for this task. The most revealing observations using the electron microscope were made by means of electron fractographic analyses.

Figure 97 illustrates a type of structure repeatedly observed on maraging steel weldmetal fracture surfaces. A very high concentration of an angular phase, closely resembling the inclusions observed in parent plate is shown. This phase was very abundant on the columnar regions of fracture surfaces of Type W9 all-weldmetal tensile specimens which exhibited such brittle behavior. Occasionally, relatively massive angular gold colored inclusion could be seen with the unaided eye. It will be shown later that preliminary work has resulted in the tentative identification of this constituent as TiN. Local concentrations of this angular phase vary considerably. As in the cases of parent plate and heat-affected zone regions, the fracture surface encompassing the angular phase is quite flat. The upper portion of Figure 97 illustrates a typical dimple structure in which the phase is absent.
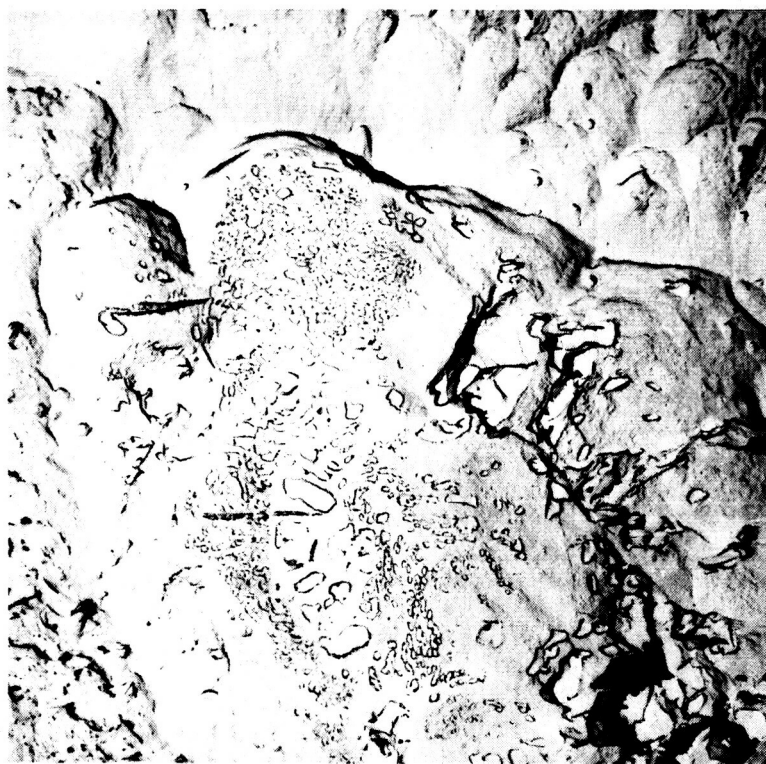
AGED MARAGING WELD DEPOSIT FRACTURE SURFACE
ILLUSTRATING A HIGH CONCENTRATION OF ANGULAR INCLUSIONS
ETCHED SURFACE - 2 STAGE PLASTIC-CARBON REPLICA
45° CHROMIUM SHADOWED
ETCHANT - CARAPELLAS REAGENT
MAG: 6,500 X

FIGURE 97

AGED MARAGING WELD DEPOSIT FRACTURE SURFACE ILLUSTRATING
THE ANGULAR PHASE AND ITS ASSOCIATED MICROSTRUCTURE
ETCHED SURFACE-2 STAGE REPLICA-45° CHROMIUM SHADOWED
ETCHANT-CARAPELLAS REAGENT
MAG: 25,900X

FIGURE 98

AGED MARAGING WELD DEPOSIT FRACTURE SURFACE ILLUSTRATING
THE ANGULAR CONSTITUENT AND ITS ASSOCIATED MICROSTRUCTURE
ETCHED SURFACE-2 STAGE PLASTIC REPLICA-45° CHROMIUM SHADOWED
ETCHANT-CARAPELLAS REAGENT
MAG. 13,670 X

FIGURE 99

<u>Weldmetal Microstructure</u> (Cont'd.)

Figures 98 and 99 illustrate higher magnification fractographs depict-
ing this angular phase, and the surrounding matrix. The fractured
surfaces were etched prior to replication in order to reveal micro-
structural details. At the higher magnification the angular phase
is seen to resemble the inclusions found in the parent material.
The angular phase has apparently ruptured by cleavage (as evidenced
by the very smooth, flat, surfaces) and is often fissured (as
evidenced by replica seepage through several of the particles).
This phase has always been observed to be virtually encircled by a
clear-etching island within the aged, precipitation-laden matrix.
The clear-etching islands seen on these fracture surfaces undoubtedly
coincide with those observed in Figure 96. A rather pronounced
interdependence appears to exist between the angular phase and the
clear-etching phase within which it resides. Some hypothetical
comments concerning this interdependency are presented in a later
section.

The angular phase and the clear etching islands are a distinctive
feature of aged weldmetal fracture surfaces. This duplex microstruc-
tural feature has not been observed in parent plate; however,
angular inclusions closely resembling this constituent have been
observed in parent plate. Furthermore, an unusually high concentra-
tion of angular inclusions in plate heat-affected zones has been
associated with especially poor fracture properties. This, therefore,
leads to the hypothesis that relatively high concentrations of the
angular phase observed on weldmetal fracture surfaces must be

6.2   <u>Weldmetal Microstructure</u> (Cont'd.)

responsible, either directly or indirectly, for the poor fracture

toughness properties of weldmetal.

7. IDENTIFICATION OF THE ANGULAR PHASE BY MEANS OF SELECTED AREA ELECTRON DIFFRACTION

This section describes preliminary work which has resulted in the tentative identification of the angular phase which appears to cause brittle behavior of maraging steel welds.

7.1 Carbon Extraction Replication Technique and Electron Diffraction

The technique employed to isolate the unknown angular phase is described in this section. First, the fracture surface to be examined is etched for approximately 60 seconds with Carapella's reagent. This is done to loosen the segregate. Then a direct carbon film is deposited on the fracture face using carbon vapor deposition. The carbon film is scribed into squares and then is removed by the application of Carapella's reagent. The unknown particles are thereby removed, attached to the carbon film. A gold film is deposited in a corner of the replica which is used to calculate the camera constant of the electron microscope. The extracted particles are identified by the use of electron diffraction techniques. A field limiting aperture was employed in the intermediate image plane, thereby restricting the diffraction area essentially to the particles isolated for identification (selected area diffraction). Unknown precipitates on the fracture surface can be analyzed by the electron diffraction pattern. Thus, important information can be obtained on influential factors affecting the path of the fracture.

7.2 Identification of the Angular Phase

In analyzing electron diffraction patterns, the following basic

relationship holds: $rd = L\lambda$, where r = radius of spot from the center, d = interplanar spacing, L = focal length of the microscope, λ = wavelength of the electron beam. The quantity $L\lambda$ is the camera constant, and may be used to evaluate the "d" value for any diffraction spot simply by measuring the corresponding "r".

Figure 100a is an electron fractograph illustrating the angular inclusion segregate on a fracture surface. This particular fractograph is characteristic of the fracture surface of a low toughness heat-affected zone specimen (Spec 7c2; $K_{IC} = 63$ KSI $\sqrt{in.}$) Figure 100b shows a fractograph of a specimen from which the segregate has been successfully extracted by the aforementioned carbon extraction-replica technique. Figure 101 shows a typical extraction fractograph from weldmetal (Type W7, Spec. 4E31). The selected area diffraction pattern, from which the following data were obtained, is given in Figure 100c, with the reference diffraction rings of gold superimposed.

The "d" value lattice spacings corresponding to the various isolated diffraction spot of the segregate are presented in Table XVIII for diffraction patterns of inclusions from plate heat-affected zone and weldmetal regions, respectively. As may be seen, almost all the "d" values of cubic titanium nitride (ASTM card 6-0642) are apparent, although two of the values lie within two of the gold reference rings. Only one of the observed diffraction spot "d" values remains unidentified. Extra spots are not uncommon in electron diffraction patterns (Reference 18).

7.2   <u>Identification of the Angular Phase</u> (Cont'd.)

The identification of the angular inclusion as titanium nitride tends

to be verified by electron microprobe x-ray analysis, as discussed

later.   This compound, as indexed, has a F.C.C. NaCl structure with

lattice parameter a_O = 4.240 A.

TABLE XVIII

COMPARISON OF INTERPLANAR SPACINGS (Å) CALCULATED FROM SELECTED AREA ELECTRON DIFFRACTION PATTERNS

Reference Ring Gold (ASTM Card 4-0784)	Replication Extraction Segregate		Titanium Nitride Ti N (ASTM Card 6-0642)	
	Heat-Affected Zone	Weldmetal		Miller Indices
	2.79	2.58		
	2.48	2.50	2.44	111
2.355				
	2.12	2.08	2.12	200
2.039				
	1.50	1.50	1.496	720
1.442				
	1.28	1.30	1.277	311
1.230		1.25	1.223	222
1.1774				
	1.06	1.09	1.059	400
	0.98	0.99	0.972	331
1.0196				
0.9358		0.96	0.948	420
0.9120				
	0.87	0.88	0.865	422
0.8325				
	0.82	0.83	0.816	333, 511

8.   <u>ELECTRON MICROPROBE X-RAY ANALYSIS</u>

This section describes work done under Douglas sponsored research
to evaluate the applicability of electron microprobe analysis for
inclusion analysis. These exploratory results lend support to the
electron diffraction data which demonstrated that TiN inclusions
represent a significant feature of weldmetal fracture surfaces.

The electron microprobe X-ray analyzer employs a fine electron beam,
approaching submicron diameter, to excite X-ray emission spectra with-
in a localized area of a specimen. A quantitative analysis may then
be made by analyzing the characteristic X-ray emitted for the presence
of elements down to atomic number ten. Some preliminary work on
maraging steel welds was conducted for Douglas in order to test the
usefulness of the microprobe as an analytical tool. Sample runs
were conducted at Materials Testing Laboratories, Division of Magnaflux
Corporation.

8.1   <u>Scanning Weldmetal Fracture Surfaces</u>

Weldmetal fracture surfaces were examined on the ARL electron micro-
probe X-ray analyzer. Because of the surface roughness inherent in
the fracture surface, the scanning images of back-scattered electrons,
sample current, and even X-ray fluorescence, as shown on the cathode
ray tube, reveal primarily the topology of the surface. Intensities
are different for separate areas of identical chemical composition
due to differences in absorption and the take-off angle caused by the
irregular, non-parallel surface. One is sometimes able to detect
rather large areas of gross compositional change by comparing back-

scattered electrons and sample current images of the same area. However, it is not readily possible to locate small area (approximately 1 micron) of even large compositional difference, or to locate large areas of small compositional differences, by this method. However, it was found quite possible to locate areas of the order of one micron with large compositional differences from the matrix by a technique of profile scanning.

If the X-ray intensity of a single element is sought, even a uniform distribution in the matrix of that element will result in a profile of varying intensities due to the effect of the rough surface mentioned before. However, if several elements are profiled for the same path and their intensities compared at various points of the path, it may be possible to detect large compositional variations even in micron or submicron areas. In the present case, titanium was profiled together with iron and nickel on weldmetal fracture surfaces. For this case, the change in intensities produced by the rough surface at a given point should be approximately the same for all three elements and in the same direction; thus, compositional variations are still detectable. In this manner, a number of areas were found where the ratios of titanium to both iron and nickel intensities were much higher than elsewhere, indicating an area considerably enriched with titanium, compared to the matrix value.

For the work to identify the titanium segregates in weldmetal, an electron beam of diameter less than 0.5 microns was used. The small specimen movement necessary to pass into and out of the high titanium

8.1   <u>Scanning Weldmetal Fracture Surfaces</u> (Cont'd.)

area leads to the conclusion that most of the areas were of micron

and submicron dimensions. The segregates appeared to be uniformly

distributed over most of the fracture surface. No reasonable attempt

can be made at a quantitative analysis of these extremely small areas

on the fracture surface. It can be said that the titanium concentration

is considerably different from the matrix and from the 100 percent

standard. A precise quantitative analysis should be easily accomplished

on particles extracted by the extraction replica technique referred to

earlier.

8.2   <u>Scanning Polished Weldmetal Surfaces</u>

With polished surfaces, cut perpendicular to the fracture surface,

scanning images revealed numerous titanium-rich segregates. Quantita-

tive measurements of such areas including the segregates were made.

Back-scattering electron images were obtained on the cathode ray tube,

showing numerous dark areas roughly several microns in diameter.

A typical image is given in Figure 102. The dark areas indicate

either the presence of an element of atomic number lower than that of

the matrix or a void. Scanning the same area with the detector for a

monochromator set for titanium gave an image with light areas (higher

titanium than matrix) which corresponded to the dark areas. The

other dark areas were shown to be voids in all cases examined. The

presence of voids is determined by viewing the sample-current image

and comparing it with the back-scattered electron image. For an

element showing a dark spot on the latter, a corresponding bright

spot will show on the sample-current image. A void will appear dark
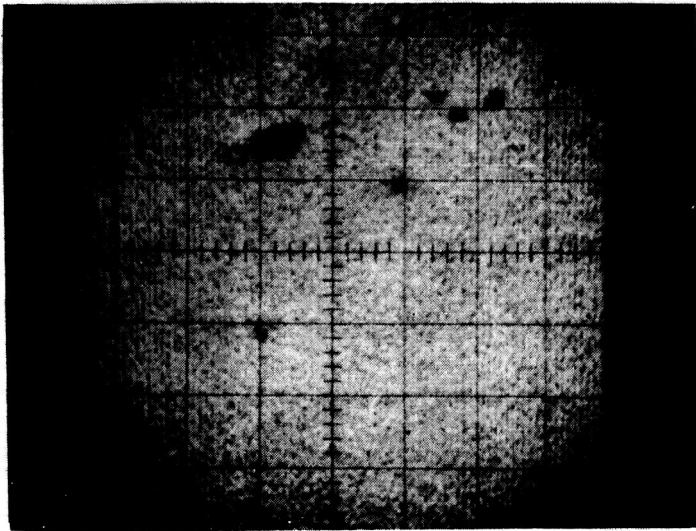
BACK-SCATTERED ELECTRON SCANNING IMAGE
A NUMBER OF DARK AREAS ARE REVEALED, WHICH ARE EITHER
SEGREGATIONS OF AN ELEMENT OF ATOMIC NUMBER
LOWER THAN THAT OF THE MATRIX OR VOIDS.

(EACH SMALL DIVISION ON GRATICULE EQUALS 2.25 MICRONS)

888x   POLISHED SPECIMEN

FIGURE 102

on both images. It appears likely that the voids formerly contained segregates which were stripped out during the polishing process.

Quantitative analyses were made on a number of the titanium enriched areas, using integrated intensities. Raw intensity data must be corrected for several factors which include background, counter characteristics, absorption, enhancement by secondary fluoresence, electron deceleration in the specimen and back-scattering of electrons.

The elements determined were, Fe, Ni, Co, Mo, and Ti. Several determinations in the matrix compared very well with the corresponding values obtained by wet chemical methods. The areas of high titanium varied up to 38 weight per cent Ti, presumably due to size fluctuations which produced a dilution effect (to be discussed shortly). Each of the titanium-enriched areas had considerably less Fe, Ni, Co, and Mo, than the matrix; this decreased with increasing titanium concentrations, but maintained essentially the same ratios with respect to each other.

In all the quantitative measurements of titanium-enriched areas, the sum of the concentrations of the elements determined plus an estimate of the trace elements (made from matrix measurements or chemical analysis) did not total 100 weight per cent. The difference corresponds very well in each case to that which would be expected if the titanium were combined in an equi-molar stoichiometry with carbon, nitrogen, or oxygen. These three elements are not capable of direct determination by electron microprobe X-ray analysis. This is in

8.2   <u>Scanning Polished Weldmetal Surfaces</u> (Cont'd.)

good agreement with the data obtained by selected-area diffraction
with the electron microscope, which revealed the extracted segregates
as being titanium nitride.

8.3   <u>Dilution Effects</u>

It is important to realize that the effective volume of electron
penetration of the specimen within which a given element will be
excited (to emit fluorescent radiation) is not the same as the
electron beam diameter, and varies with the element and electron-
accelerating voltage. It is, of course, these areas to which the
quantitative analysis applies for a given element. In general, the
effective areas for the present determination were several microns
in diameter, even at reduced accelerating voltage (25 reduced to
15 KV). Thus, generally, if the segregate in question is smaller
than the effective areas of excitation, its true composition cannot
be determined because of a dilution effect of the matrix. However,
lower limits for each element in the segregate may be determined.
Most of the segregates in the few specimens tested appear to be in
this range, i.e., generally less than several microns.

As in the case of the segregates on the fracture surface, the size is
often less than a micron, and the distribution of titanium enriched
areas is rather uniform throughout the polished specimen surface.
Quantitative data are strongly suggestive on TiN segregation,
supplementing the electron diffraction findings.

9.   <u>THE INFLUENCE OF TiN AND RELATED FACTORS ON MARAGING STEEL WELD
      PROPERTIES</u>

Results presented in previous sections show that a probable relation-
ship persists between the angular phase recurrent on maraging steel
fracture surfaces and low plane-strain fracture toughness. This
appears to be especially true in weldmetal fracture surfaces. The
preliminary work on the identification of this phase shows that the
compound TiN is involved either directly or indirectly in this
undesirable behavior. This section presents a brief discussion of
the possible effects of TiN in the maraging class of alloys. A
hypothesis is presented whereby the relative independence of fracture
toughness on thermal treatments may be rationalized.

9.1   <u>Properties of TiN and TiC</u>

Titanium nitrides and carbides Ti (C,N,) are commonly present as
inclusions in steels containing these alloying elements (References
21 and 22). The nitrogen is usually introduced as a result of melt-
ing practice. Once such particles have formed in the solid matrix,
they cannot be readily eliminated because of their high chemical
stability (References 15 and 19). In nickel alloys these particles
have been shown to be stable up to the melting point of the alloy
(Reference 20). Thus, it is unlikely that such inclusions in maraging
steels could be eliminated by high temperature thermal treatment.
TiC and TiN form a pseudo-binary isomorphous system, Figure 103.
Both components are of the FCC-NaCl structure, and the anions subs-
titutionally replace each other in the lattice. Some additional
properties of interest are given in Table XIX. Both the carbide and

PHASE DIAGRAM OF TiC AND TiN
BASED ON AVAILABLE DATA

FIGURE 103

192
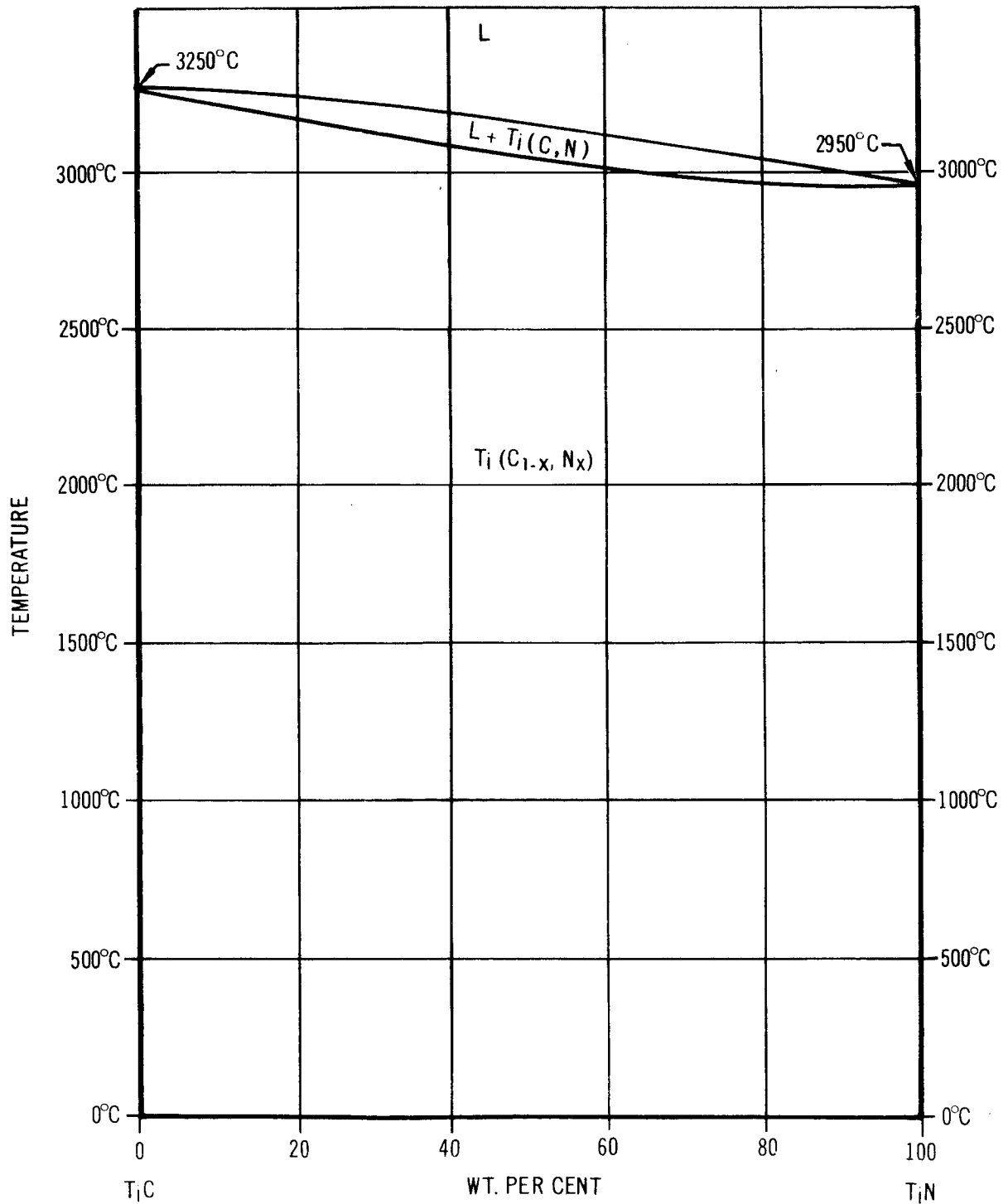
9.2   TiN in Weldmetal (Cont'd.)

Such reverted austenite may not transform to martensite upon cooling

to room temperature until the localized concentration has decreased

to the point where the Ms of the austenite is equal to or greater

than room temperature, (Reference 21). Thus, until a critical

nitrogen concentration is attained, the amount of austenite tends to

increase with increasing aging time. Carbon probably has a similar

effect.

9.3   Possible Effects of Austenite in Weldmetal

The austenite, retained or reverted during aging, may possess some

interesting properties. Reverted austenite in 18 Ni-9Co-5Mo alloy

and very likely also in 18Ni-7Co-5Mo, may be transformed back to

martensite by plastic straining. The resultant martensite, despite

the expected chemical non-homogeneity, is capable of a normal aging

response (Reference 22).

This effect is of interest in weldmetal, since plastic deformation

could possibly induce the transformation of austenitic islands to an

alloy-enriched martensite and therefore change its mechanical proper-

ties. Such alloy-enriched martensite would be expected to be relative-

ly brittle. Normally, the presence of austenite would be expected to

increase the ductility of the weldmetal. However, the presence of

relatively large concentrations of nitrogen could result in low

fracture toughness arising from the nitrogen in solution as well as

from the presence of the brittle TiN phase.

9.4.   Toughness Degredation and TiN

In summation, the following hypothetical model relating to the
formation and influence of titanium nitride appears to emerge.

1. Titanium nitrides present as inclusions in the parent plate,
    electrode wire, or originating from other sources find their
    way into molten weld puddle. Because of their high thermal
    stability, and the rapidity with which the weld puddle solidifies,
    the nitrides tend to remain essentially intact. Partial solution
    and re-precipitation upon cooling is possible.

2. The titanium nitrides tend to migrate to the liquid phase in
    the molten weld puddle. This leads to locally high concentrations
    of titanium nitride. Partial solution of the nitrides provides
    soluble nitrogen which tends to promote the formation of stable
    austenite. Such stable austenite may form upon direct solidifica-
    tion of the weld puddle or upon subsequent aging and re-cooling to
    room temperature.

3. As a result of the mechanisms postulated in (1) and (2) a semi-
    continuous dispersion of titanium nitrides, surrounded by alloy
    enriched austenite, may develop. Such semi-continuous networks
    found in aged weldmetal appear to provide favored propagation
    paths for fracture.

Several alternatives may be offered to explain the apparently damaging
effects of the semi-continuous titanium nitride inclusions. First,
damage may be produced simply because of the presence of the brittle
TiN phase through which crack propagation may occur at a relatively

low energy expenditure. This effect is personally favored by the authors as the most important. As may be recalled, low toughness fractures were occasionally observed in heat-affected zone regions. These regions were characterized by high concentrations of titanium nitrides. However, unlike the weldmetal the nitrides were not surrounded by light etching islands (stable austenite or alloy enriched, unaged martensite). Thus it appears that the nitrides alone are responsible for the impairment of toughness. This conclusion is further supported by the observed effects of a variety of post weld thermal treatments.

As may be recalled, plane-strain fracture toughness of weldmetal was substantially unaffected by the duration or temperature of aging (as well as welding procedure). Nor did re-solution heat treatments change toughness significantly. The relative constancy is readily explainable in terms of the thermal stability of the titanium nitride network. Although precipitation, austenite reversion, and other reactions may occur as a result of the thermal treatments employed, very little change would be expected in the dispersion of titanium nitride. Thus the relative constancy of toughness may be explained by the thermal stability of the titanium nitride network.

A second mechanism may involve the presence of alloy-enriched (especially with nitrogen) austenite which may surround the titanium nitride inclusions. The possible spontaneous strain-induced transformation of such enriched austenite to relatively brittle martensite, during the course of crack propagation, could further

9.4 <u>Toughness Degredation and TiN</u> (Cont'd.)

degrade toughness.

As a third possibility, unaged alloy-enriched martensite surrounding the nitrides may produce additional damage.

Possibly all three mechanisms may be involved, however basic to all three is the predominant role of titanium nitride.

The precise effects of titanium nitride and the associated mechanisms responsible for the toughness degredation of welds cannot be positively stated at present. Critical testing of the postulated model is necessary. Such additional experimentation could lead to a clearer understanding of the phenomenon. Perhaps of even more importance, such work could provide methods of substantially improving the fracture toughness properties of welds.

10. <u>SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS</u>

Significant observations, conclusions, and pertinent recommendations
may be summarized as follows:

1. Different heats of nominally 250 KSI, 18Ni-7Co-5Mo 3/4-in thick
airmelted plate have been shown to vary substantially in aging
response. Both tensile and fracture toughness properties may
exhibit significant differences, after identical aging treatments,
despite relatively small chemical composition differences. The
causes of these variations should be thoroughly investigated.
Presently, plate from any heat must be individually tested to
assure conformance with the required specifications.
Compliance with chemical composition specifications, alone,
cannot be relied upon.

2. Prolonged aging of plate tends to degrade toughness. The
mechanisms responsible for the degradation are unknown and should
be investigated. The decrease in toughness may not always be
associated with a concomitant increase or decrease in strength.

3. Differences between transverse and longitudinal properties for
plate were generally small. Tensile strength was usually higher
and toughness lower for the transverse orientation.

4. Differences of $75^{\circ}F$ in the aging temperature (875 versus 950°)
may produce tensile strength differences of up to 40,000 psi in
plate. Special aging techniques may have to be developed for
large space launch vehicle structures to assure the required
temperature control.

5. Plate hardness does not correlate very well with tensile strength.

6. A subsize partial thickness crack (PTC) fracture toughness specimen was developed and evaluated. The results showed that plane strain, K_{IC} (modified), and net fracture stress data generated using the subsize specimen correlated well with results obtained using substantially larger specimens. Theoretical analysis of specimen size effects is required.

7. Weldmetal and heat-affected zone cracking were not observed in welds deposited without preheat. Rigid control was, however, exerted on the hydrogen potential of the arc atmosphere.

8. Porosity problems were encountered in some of the welding studies. Although empirically guided modifications in welding procedures were able to eliminate the problem, the causes of porosity are not known. Work on the mechanisms of porosity formation in maraging alloys is worthy of study.

9. Tensile efficiency of weldmetal, deposited using a titanium enriched (about 1%) filler wire, generally exceeded 90 percent after most aging treatments and approached 100 percent after some.

10. Up to about 10 percent strength loss may occur in plate heat-affected regions of welds. The strength in these impaired heat-affected regions may be increased by prolonged aging to within 5 percent of the parent plate strength.

APPENDIX II (Cont'd.)

APPLICATION SPECIFICATIONS

The following specification, of issue in effect on date of invitation for bids, form part of this specification, as applicable:

Aeronautical Material Specification

AMS 2815-A	Identification and Packaging Welding Wire

Military Specification

MIL-E-18193A	Steel, and Alloy Steel, Bare Coiled.

American Society for Testing Materials

ASTM E 45-51	Determining Inclusion Content of Steel

TECHNICAL REQUIREMENTS

Micro-Cleanliness

The micro-cleanliness shall be determined according to ASTM specification ASTM E 45-51 method A with ratings no poorer than:

	Thin	Heavy
A	1.0	1.0
B	1.0	1.0
C	1.0	1.0
D	1.0	1.0

Cast

Wire shall have imparted to it a curvature such that a specimen 10 to 12 feet long, when cut from the spool and suspended freely from its approximate midlength, shall form a circle not less than 20 inches and not greater than 36 inches in diameter. If

APPENDIX II (Cont'd.)

APPLICATION SPECIFICATIONS

The following specification, of issue in effect on date of invitation for bids, form part of this specification, as applicable:

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Micro-Cleanliness

The micro-cleanliness shall be determined according to ASTM specification ASTM E 45-51 method A with ratings no poorer than:

	Thin	Heavy
A	1.0	1.0
B	1.0	1.0
C	1.0	1.0
D	1.0	1.0

Cast

Wire shall have imparted to it a curvature such that a specimen 10 to 12 feet long, when cut from the spool and suspended freely from its approximate midlength, shall form a circle not less than 20 inches and not greater than 36 inches in diameter. If

the curvature of the wire results in a coil of more than 1-1/2 turns, the excess shall be clipped off and the wire resuspended from its new approximate midlength.

Helix

A specimen cut and suspended as above and measured between adjacent turns shall show a separation not greater than 4 inches.

Layer Winding

Wire shall be closely wound in layers but adjacent turns within a layer need not necessarily be touching; shall be wound so as to avoid producing kinks, waves, and sharp bends; and shall be free to unwind without restriction caused by overlapping or wedging. The outside end of the spooled wire shall be so placed that it may be readily located.

Heat

Wire on each spool shall be of one continuous length from the same heat of material. Cut lengths in any one package shall be from the same heat of material.

Hardness

Wire hardness shall not exceed 34 Rockwell C or equivalent.

QUALITY

Material shall be vacuum melted. The product shall be uniform in quality and condition, clean, sound, smooth, and free from foreign materials and from internal and external imperfections detrimental to welding operations, operation of welding equipment, or properties of the deposited weld metal.

APPENDIX II (Cont'd.)

SIZES AND TOLERANCES

Unless otherwise specified, wire shall be supplied in the following sizes
and to the tolerances shown:

Diameter

Form	Nominal Diameter Inch	Tolerance, Inch plus and minus
Cut Length	0.045, 0.062, 0.093, 0.125	0.003
Spools	0.030, 0.035, 0.045, 0.062, 0.093	0.001
Spools	0.007, 0.010, 0.015, 0.020	0.0005

Length

Straight lengths shall be furnished in 18, 27, or 36-inch lengths as
ordered, and shall not vary more than $\pm$ 1/4 inch from the length ordered.

REPORTS

Unless otherwise specified, the vendor of the product shall furnish with
each shipment three copies of a report of the results for chemical
composition of each heat in the shipment and a statement that the product
conforms to the technical requirements of this specification. This report
shall include the purchase order number, material specification number,
nominal size, and quantity from each heat.

Unless otherwise specified, when parts made of this wire or assemblies
requiring the use of this welding wire are supplied, the part or assembly
manufacturer shall inspect each lot of wire to determine conformance to
this specification and shall furnish with each shipment three copies of a
report stating that the wire conforms to the requirements of this specifi-
cation. This report shall include the purchase order number, part or
assembly number, and quantity.

PACKAGING AND MARKING

Packaging shall be accomplished in such a manner as to ensure that the wire, during shipment and storage, will be protected against machinical injury, contamination, and moisture.

Cut Lengths

Wire shall be furnished in standard containers of approximately 5, 10, 50, or 100 lb net weight, as specified.

Cut lengths shall be marked (code 615), cleaned, and packaged in accordance with the latest issue of AMS 2815.

Spooled Wire

Spools shall be of such materials and construction as to provide adequate strength and rigidity to prevent damage or distortion in normal handling and use, and to insulate the wire from the spindle. Unless otherwise specified, wire shall be furnished on spools of approximately 25 lbs ± 1 lb net weight.

Marking

Both sides of each spool for spooled wire and each bundle and container for cut wire shall be permanently and legibly marked with the following information:

> 18% Maraging Steel Wire
> DMS 1836 (revised 4/11/63)
> Cobalt Content_____
> Titanium Content_____
> Carbon Content_____
> Size_____
> Quantity_____
> Heat Number_____

APPENDIX II(Cont'd.)

Purchase Order Number_____

Manufacturer's Identification_____

REJECTIONS

Wire not conforming to this specification or to authorized modifications
will be subject to rejection.

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APPENDIX III

PROCEDURE FOR CRACKING PTC COUPONS

Code 18355

DLP 13.822

DOUGLAS AIRCRAFT COMPANY, INC.

ISSUE OF 6-27-62

PAGE 1 OF 12

DOUGLAS LABORATORY PROCEDURE

TITLE: **TECHNIQUE FOR MAKING SHALLOW-CRACKS IN SHEET METAL TENSILE SPECIMENS**

A. **SCOPE & USE**:

This Laboratory Procedure describes the method for making shallow-cracks in sheet metal tensile specimens.

B. **EQUIPMENT**:

1. 3600 RPM 50 lbs. capacity Krouse Sheet Flexure Fatigue Machine.

2. Two wedge type support blocks to clamp the specimen (Figures 1 and 2). These blocks should be made of a material that is as hard or harder than the specimen material. 4340 steel support blocks hardened to RC 53 have been used successfully for high-strength steel specimens.

3. Two adapter blocks to attach the specimen to the connecting rod of the fatigue machine. (Figures 3 and 4).

4. 40 power microscope with an eyepiece scale graduated in 0.001".

C. **SPECIMEN PREPARATION**:

1. The specimen used is a pin-loaded tensile specimen as shown in Figure 5.

2. The specimen which is to be cracked is ground or sanded so that the grinding or sanding striations are in the longitudinal direction of the specimen (normal to the crack length). It may be necessary to grind both sides of the specimen to maintain flatness. In grinding, not more than 0.001 inch thickness of material is removed with one pass. Preferably, high-strength steel is ground in the annealed condition to prevent grinding cracks and burning.

3. An electrical discharge machined starter notch (0.003 inch deep, 0.004 inch wide and 0.006 inch long) is made in the specimen at the desired location of the shallow-crack.

APPENDIX III (Cont'd.)

C. (Cont'd)

4. The specimen is then heat treated to the desired strength level, if required, using heat treat fixtures where necessary to maintain flatness.

5. The sharp corners and the specimen surface, on which the shallow-crack is to be introduced, are polished using No. 100 abrasive cloth first and finished with No. 1 abrasive polishing paper. The specimen is always polished in the longitudinal direction of the specimen.

D. PROCEDURE:

1. The specimen is placed (polished surface facing up) between the two wedge-shaped support blocks and its position adjusted so that the electrical discharge machined starter notch is located approximately 1/16 inch directly in front of the tip of the top wedge shaped block. (Figures 6 and 7).

2. The free end of the specimen is attached to the connecting rod of the fatigue machine by means of the two adapter blocks. (Figures 6 and 7).

3. By means of an adjustment screw near the fixed end of the specimen, the height of the specimen is adjusted so that the stress on the polished top surface of the specimen is always tension, never compression.

4. The eccentric of the fatigue machine is adjusted so that the initial crack occurs within a convenient time, about 3 to 5 minutes. An eccentricity of 16 to 20 divisions (deflection of 0.48 to 0.59 inch respectively) is satisfactory for high-strength steel.

5. The microscope is focused on the polished top surface of the specimen so that the electrical discharge machined starter notch is visible in the center of the field of view. (Figure 7).

APPENDIX III (Cont'd.)

D. (Cont'd)
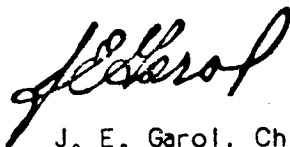
6. The fatigue machine is then turned on and allowed to run for a
short time, one or two minutes. The fatigue machine is then
stopped and the specimen surface viewed through the microscope
to see if a crack has initiated from the starter notch. If there
is no crack, the fatigue machine is run again for a short time and
the specimen surface viewed again. This procedure is repeated
until a crack has initiated from the starter notch. The crack
length is then measured with the graduated eyepiece of the micro-
scope. Cycling is continued until the desired crack length is
obtained. Approximate relations between crack length and crack
depth for 0.070 inch high-strength steel, 0.050 inch 6Al-4V
Titanium, 0.050 inch 5Al-2.5 SN Titanium, 0.100 inch and 0.250 inch
2014-T6 Aluminum are presented in Figures 8 and 9.

7. The crack length and number of cycles are recorded and the specimen
is removed from the fatigue machine.

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Materials Research & Production Methods
Missile & Space Systems Division

R. A. Simpson, Chief
Materials Research & Process Engineer
Aircraft Division

J. E. Garol, Chief
Materials & Process Engineer
Tulsa Division

SLP:bn

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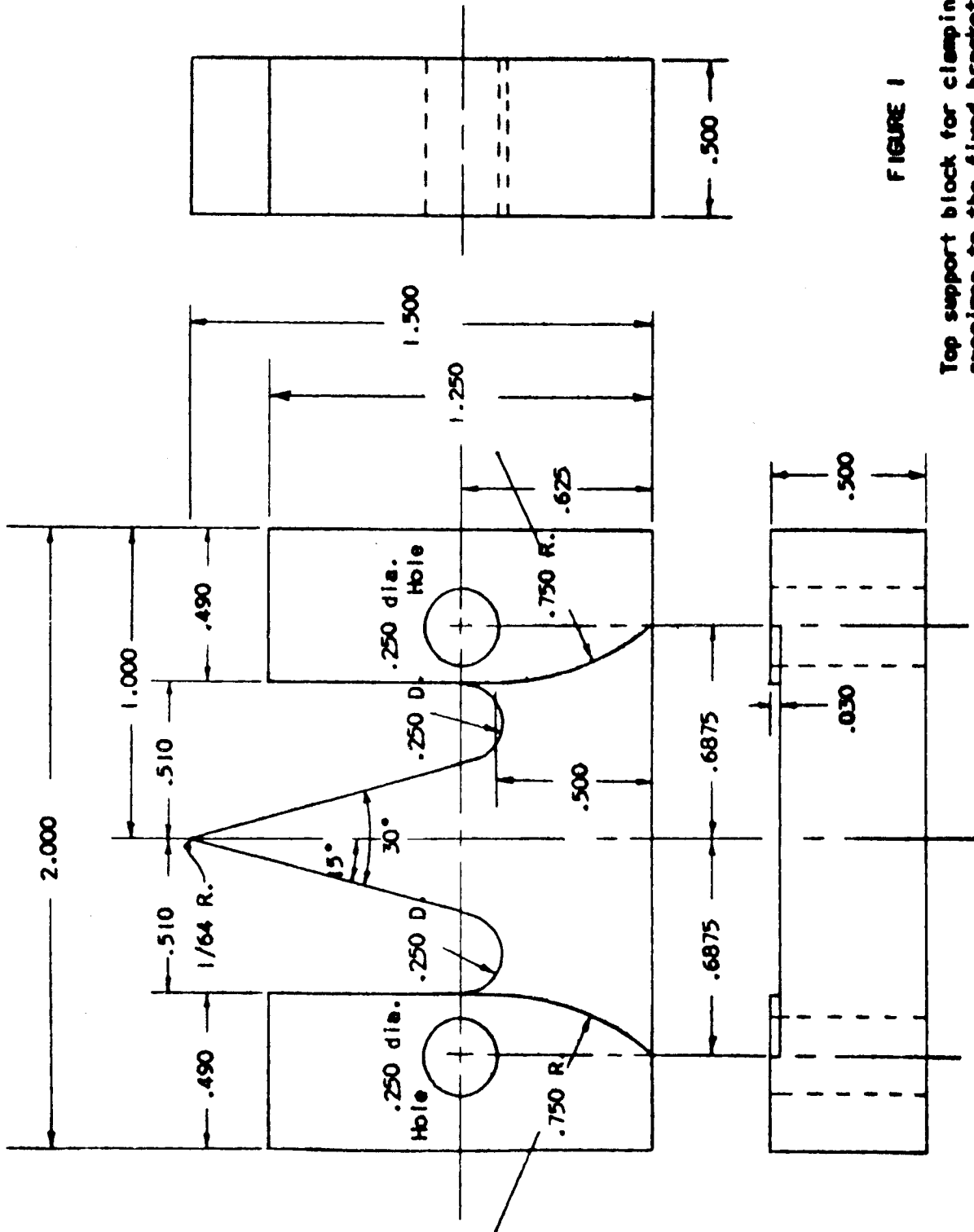
APPENDIX III (Cont'd.)

FIGURE 1

Top support block for clamping the specimen to the fixed bracket of the fatigue machine.
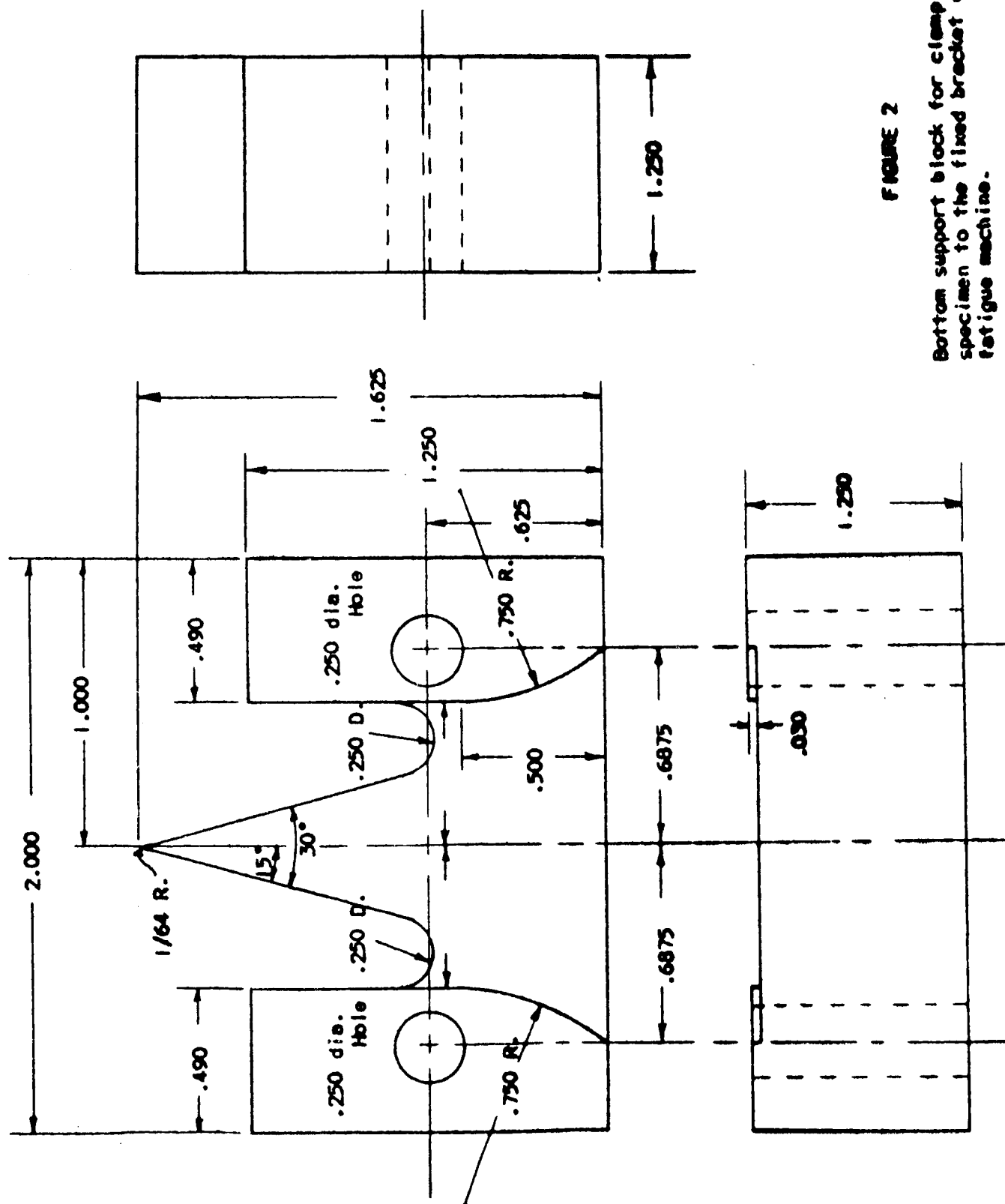
APPENDIX III (Cont'd.)

FIGURE 2

Bottom support block for clamping the specimen to the fixed bracket of the fatigue machine.

224
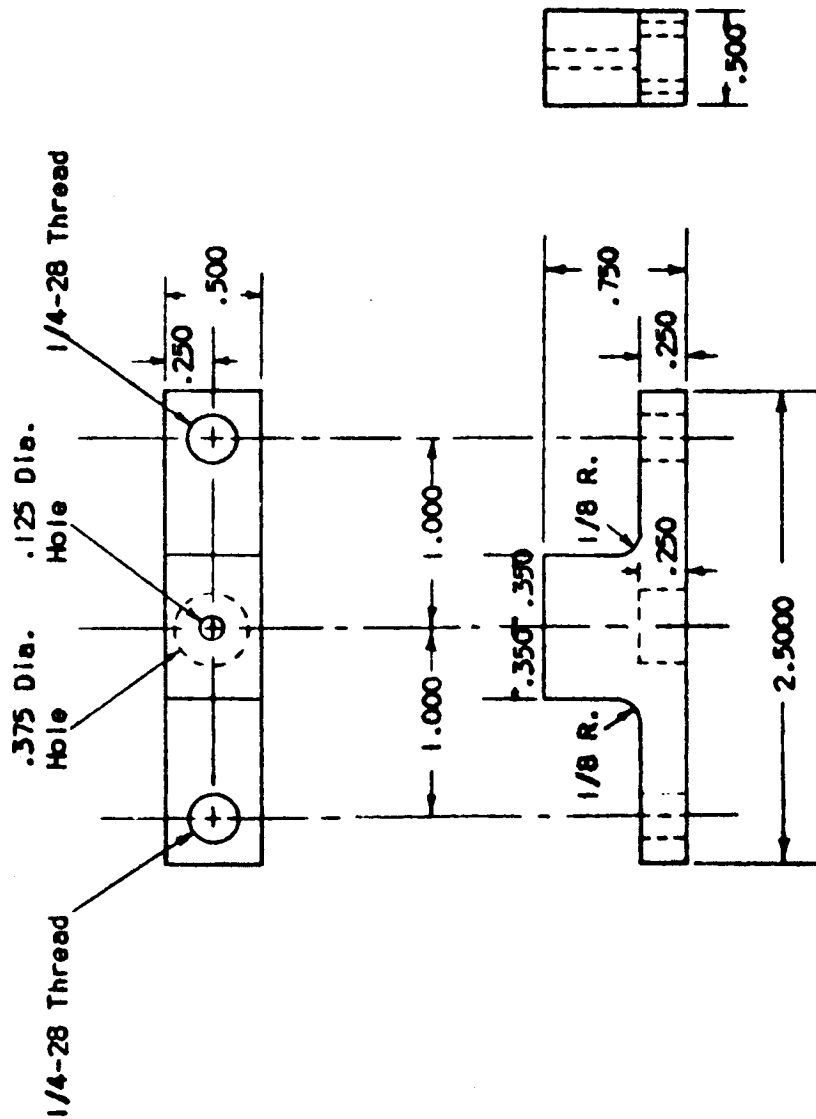
APPENDIX III (Cont'd.)

FIGURE 3

Top adapter block for attaching the specimen to the connecting rod of the fatigue machine.

APPENDIX III (Cont'd.)
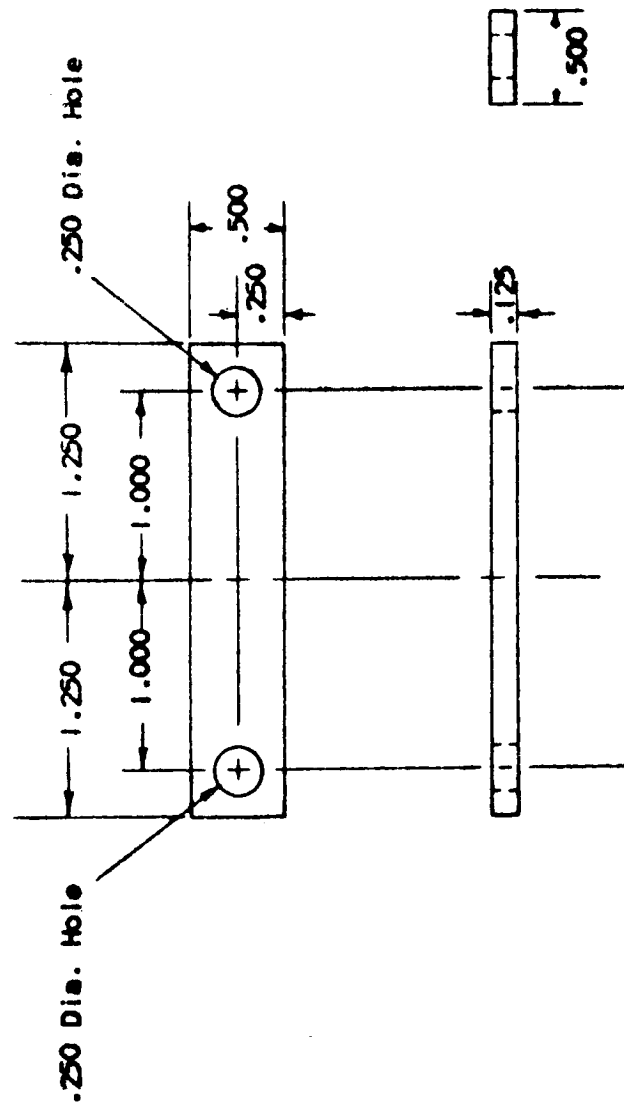
FIGURE 4

Bottom adapter block for attaching the specimen to the connecting rod of the fatigue machine.

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FIGURE

SHALLOW CRACKED SHEET TENSILE SPECIMEN
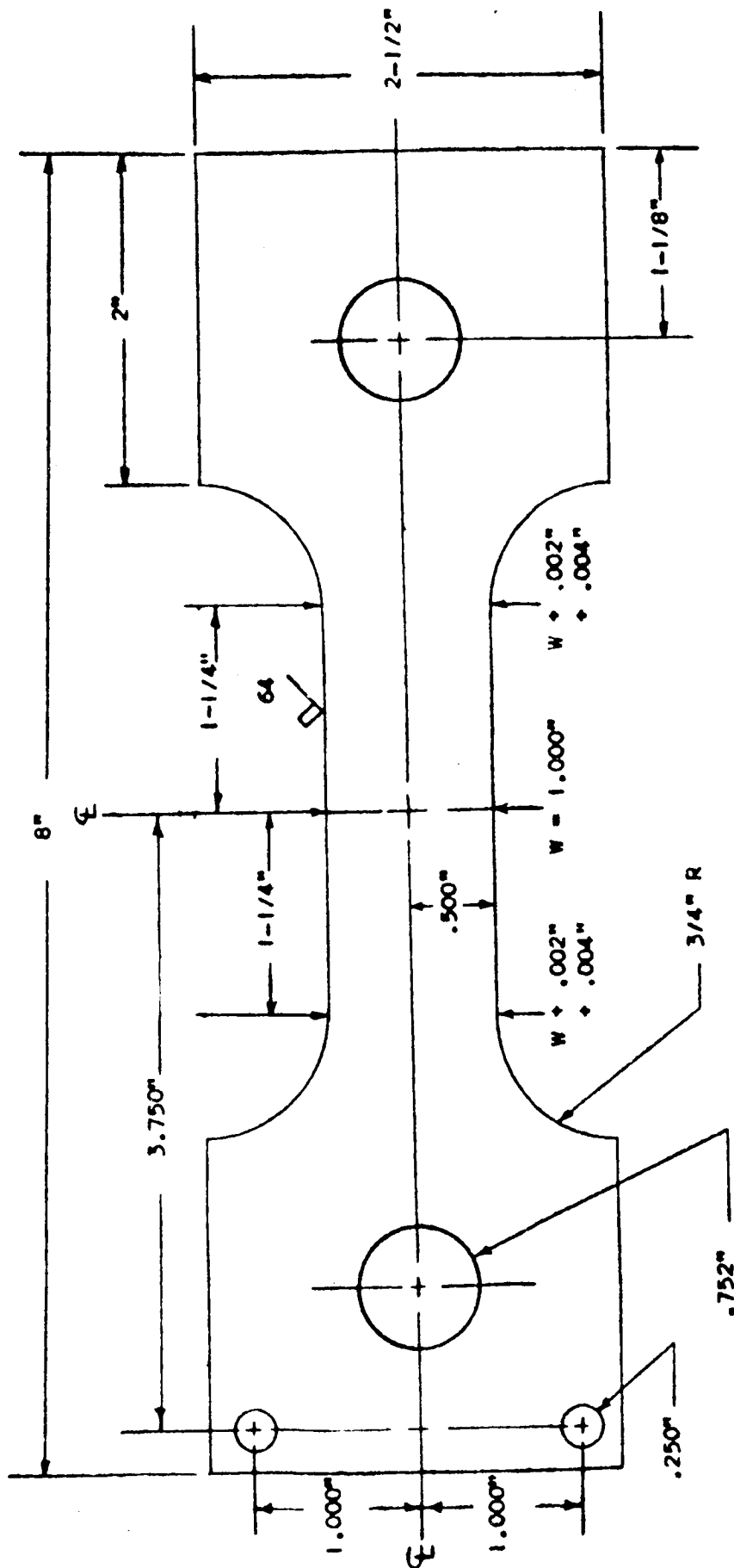
TOLERANCES

Fractions ± 1/32"

Decimal ± 0.002"

Unless otherwise specified.

NOTES

1. Gradual equal taper on both sides from outer ends of reduced section towards center as shown with no abrupt changes.

2. Edges of reduced section to be left sharp.

3. Finish is to be RMS 125 except as shown.

4. Holes must be on ℄ within 0.002".

APPENDIX III (Cont'd.)

CONNECTING ROD

FIXED END
SUPPORT BLOCK

SPECIMEN

FREE END
BLOCK

FIXED END
SUPPORT BLOCK

FREE END
BLOCK
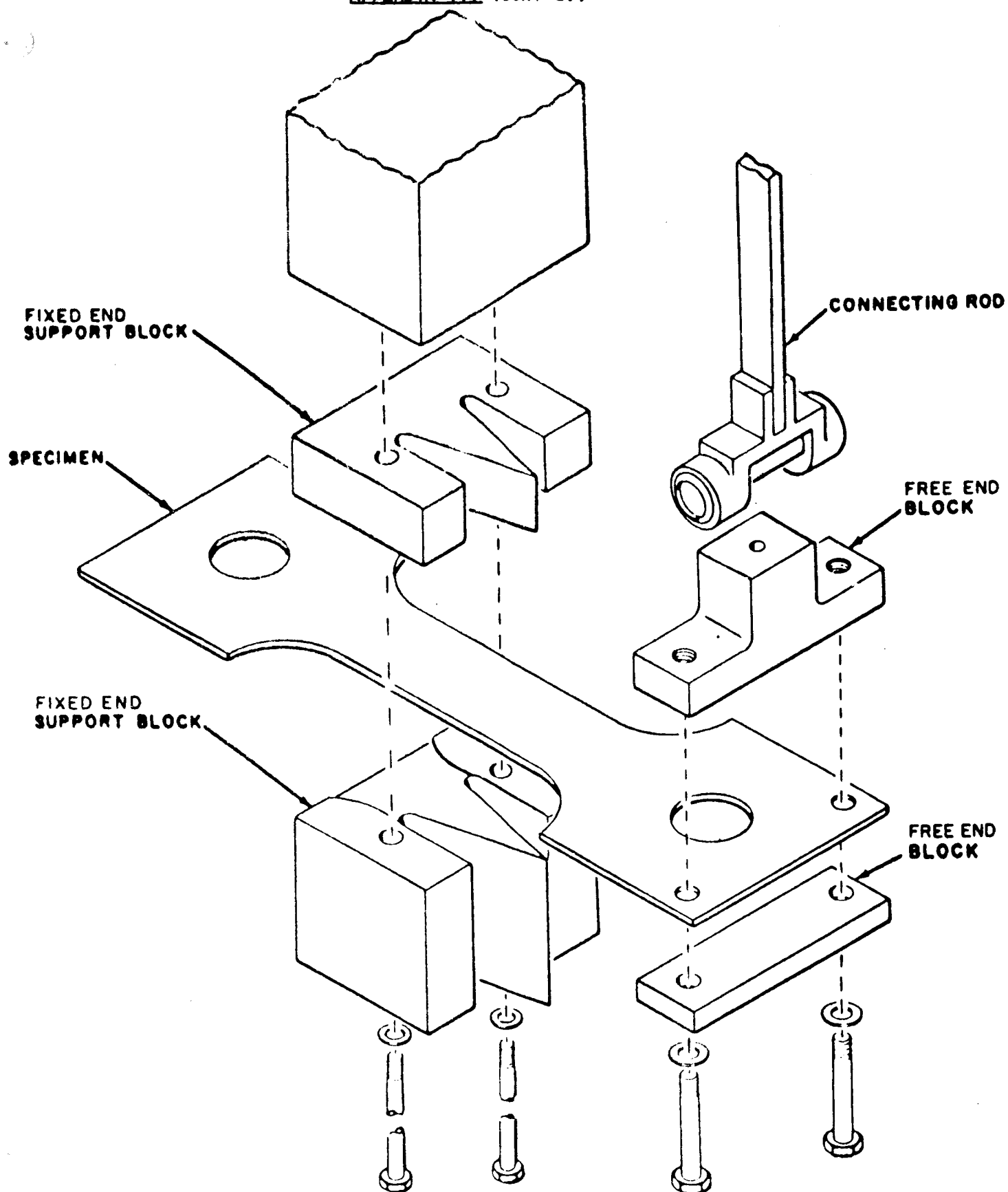
FIGURE 6

Set-up for making shallow crack (exploded view).

APPENDIX III (Cont'd.)
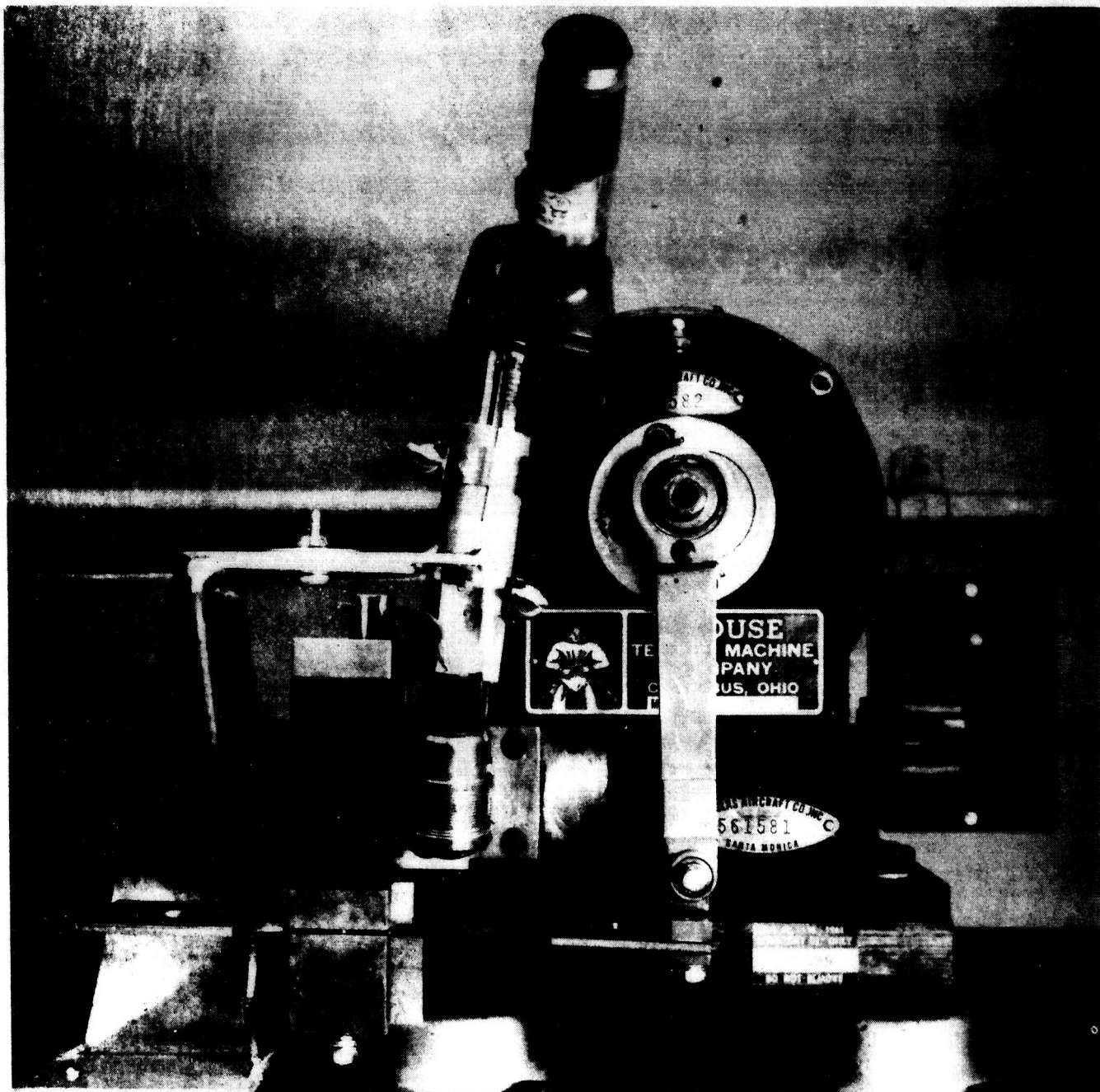
SM 350251

FIGURE 7

SET-UP FOR MAKING SHALLOW CRACKS (FRONT VIEW).

Relation between crack length and crack depth of shallow cracks in .070"
thick 4340 and H-11 steels H.T. 260 to 280 ksi.

CRACK LENGTH, mils vs CRACK DEPTH, mils

4340 Steel ⊙
H-11 Steel ●
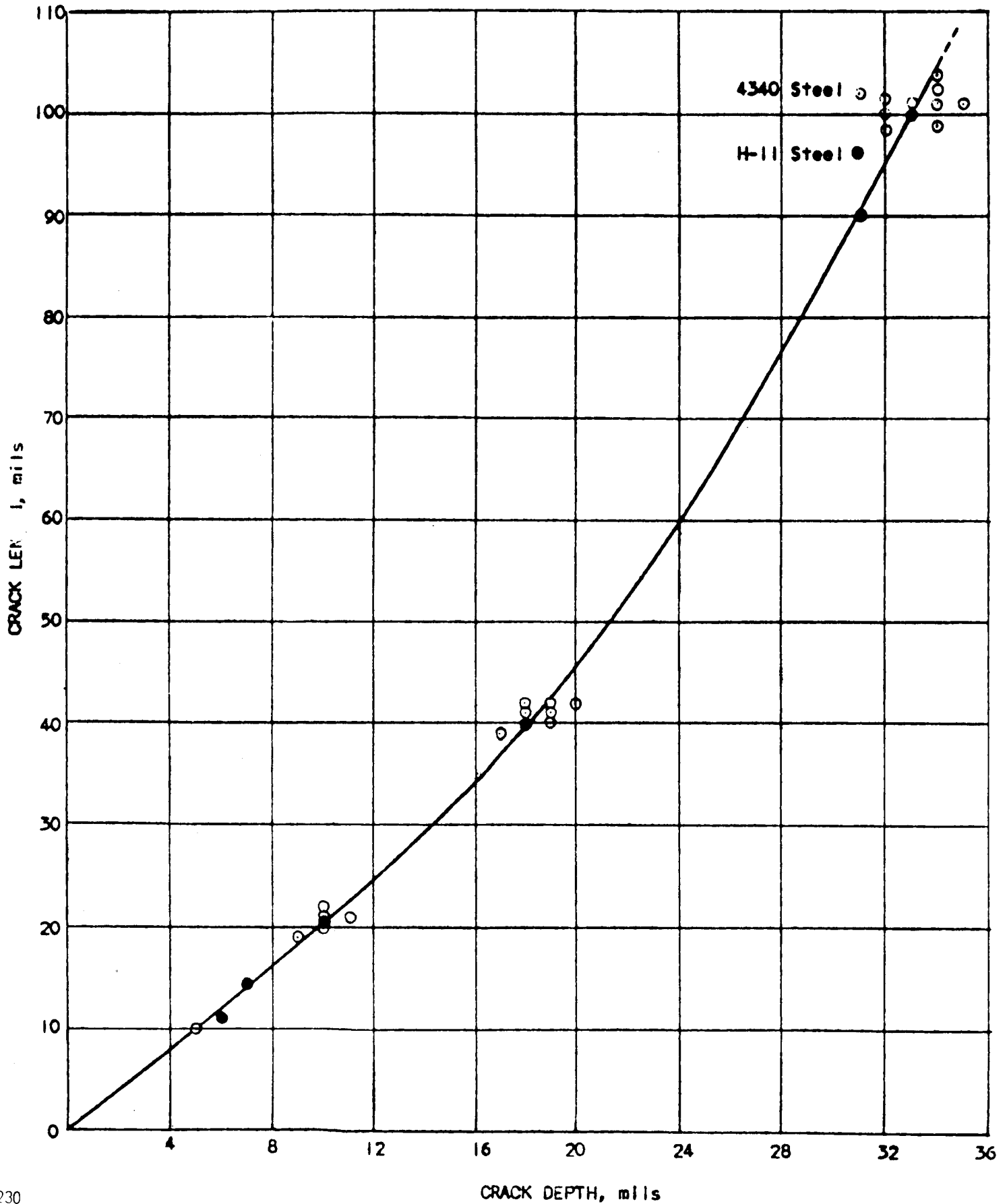
RELATION BETWEEN CRACK LENGTH AND CRACK DEPTH OF SHALLOW-CRACKS IN
0.050 IN. 6AL-4V TITANIUM, 0.050 IN. 5AL-2.5 SN TITANIUM, 0.100 IN.
AND 0.250 IN. 2014-T6 ALUMINUM.

SHALLOW-CRACK LENGTH, INCH

SHALLOW-CRACK DEPTH, INCH
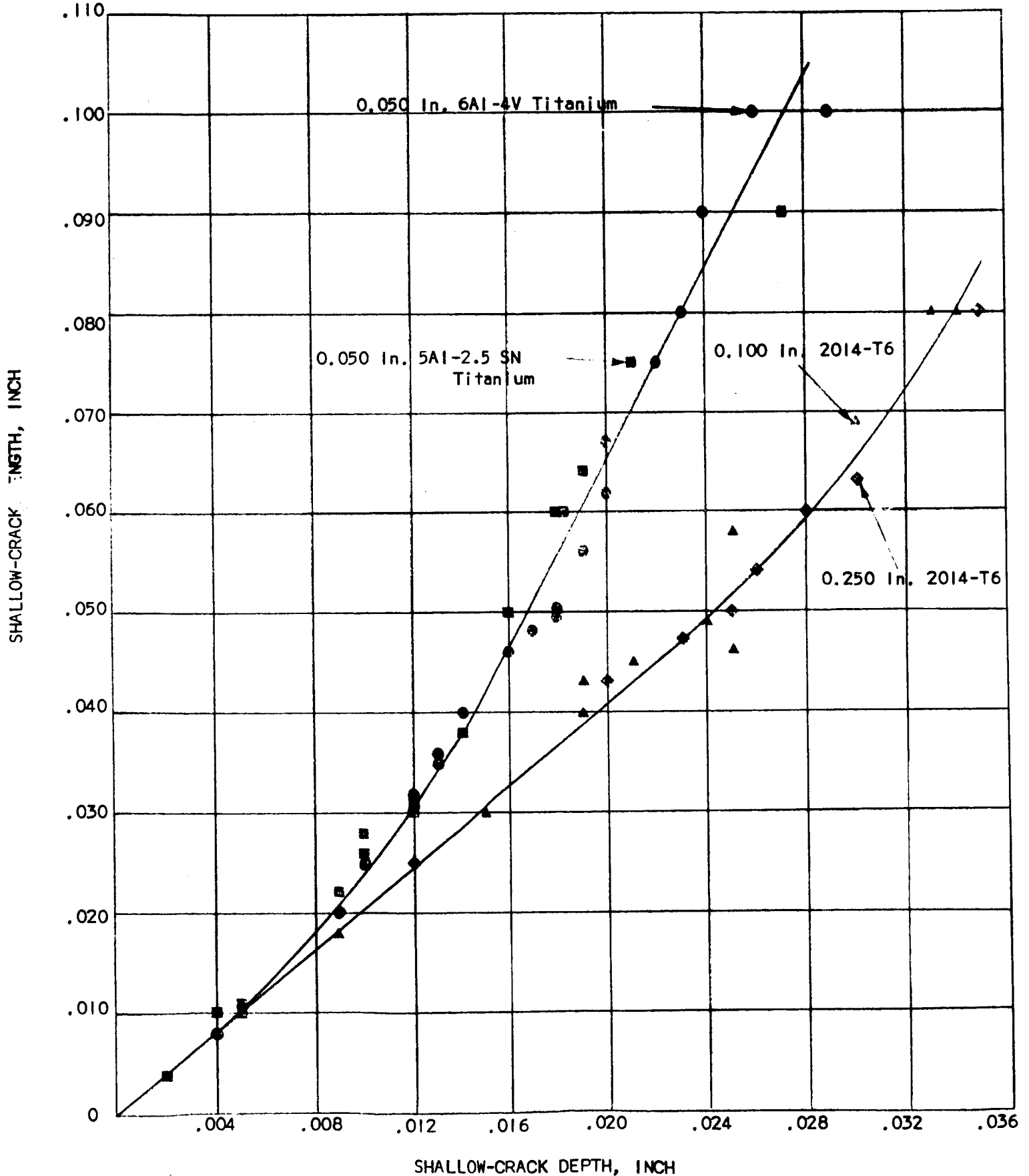
APPENDIX IV

PLATE UNIAXIAL TENSILE DATA

APPENDIX IV - PLATE TENSILE DATA SUMMARY

UNIAXIAL TENSILE DATA - HEAT I PLATE

SPEC. NO.	AGING TEMP., °F	TIME AT TEMP. HRS.	0.2% YIELD STRESS, (KSI)	ULTIMATE STRESS, (KSI)	% ELONG. (2-IN. GAGE)
2-4	875	3	247.3	252.5	10.0
2-8	875	3	244.8	250.8	11.0
2-10	875	3	247.8	253.7	10.0
2-22	875	8	NA	263.9	8.0
2-23	875	15	NA	268.3	9.0
2-6	900	3	257.7	264.2	8.5
2-7	900	3	259.1	264.4	8.5
2-8	900	3	260.7	265.2	9.0
2-16	900	8	NA	266.6	9.0
2-24	900	8	NA	265.7	8.0
2-25	900	8	NA	264.0	9.5
2-26	900	15	NA	269.1	9.0
2-5	925	3	263.5	267.2	9.0
2-12	925	3	265.7	269.2	9.0
2-13	925	3	259.7	267.7	10.0
2-28	925	8	NA	266.5	7.5
2-29	925	15	NA	266.5	9.0
2-30	950	3	NA	269.0	8.0
2-17	950	8	NA	261.6	10.0
2-31	950	8	NA	263.5	8.5
2-32	1000	1	NA	255.0	9.0
2-18	1000	3	NA	252.4	9.5
2-33	1000	3	NA	255.0	10.0
2-19	1000	8	NA	242.9	12.0

NOTES:

1. All results obtained with .505-in. diameter specimens

2. Not available

3. All specimens longitudinal

TENSILE DATA ON HEATS A AND B PLATE
TO CHECK SPECIFICATION CONFORMANCE

SPEC. No.	SPECIMEN ORIENTATION	0.2% YIELD STRESS, (KSI)	ULTIMATE STRESS, (KSI)	% ELONG. (2 in. Gage	% RED. IN AREA
HEAT A PLATE TENSILE DATA					
AP 31	L	253.0	259.0	11.0	45.5
AP 32	L	252.0	258.5	11.0	44.9
AP 33	L	253.6	258.8	11.0	44.0
AP 34	T	255.0	260.8	8.0	32.5
AP 35	T	253.0	260.0	10.0	36.6
AP 36	T	254.0	260.3	9.0	38.8
HEAT B PLATE TENSILE DATA					
P-31	L	254.5	264.0	9.0	41.9
P-32	L	257.0	265.0	11.0	41.3
P-33	L	253.5	263.0	8.0	38.5
P-34	T	265.5	270.0	8.0	33.4
P-35	T	264.0	267.5	8.0	33.4
P-36	T	259.0	269.0	7.0	34.4

NOTES:

1. L = Longitudinal

   T = Transverse

2. All results obtained with 0.505-in. diameter specimens

3. Aged at $900^{\circ}F$ for 3 hours

UNIAXIAL TENSILE DATA - HEATS-A AND B PLATE AGED AT 950°F

HEAT-A PLATE

SPEC. NO.	TIME AT TEMPERATURE (HOURS)	SPECIMEN ORIENTATION	0.2% YIELD STRESS (KSI)	ULTIMATE STRESS (KSI)	% ELONG. (IN 2")	% RED. IN AREA
AP217	1	L	247.8	255.5	10.0	42.2
AP218	1	L	248.3	254.7	10.0	49.6
AP241	1	T	247.6	254.5	9.0	39.0
AP242	1	T	247.0	254.6	8.0	39.0
AP219	3	L	251.7	260.1	11.0	48.1
AP220	3	L	250.6	260.4	10.0	44.2
AP243	3	T	254.2	261.3	10.0	38.7
AP244	3	T	254.7	261.6	7.0	36.6
AP221	6	L	250.6	256.3	10.0	39.2
AP222	6	L	247.8	256.3	11.5	44.7
AP245	6	T	251.7	259.8	10.0	35.7
AP246	6	T	252.7	259.6	10.0	35.7
AP223	12	L	239.9	247.6	12.0	37.4
AP224	12	L	240.7	248.1	13.0	50.9
AP247	12	T	243.5	252.4	10.5	39.1
AP248	12	T	241.9	251.2	10.5	41.1

HEAT-B PLATE

SPEC. NO.	TIME AT TEMPERATURE (HOURS)	SPECIMEN ORIENTATION	0.2% YIELD STRESS (KSI)	ULTIMATE STRESS (KSI)	% ELONG. (IN 2")	% RED. IN AREA
P29	1	L	252.6	263.4	10.0	43.9
P210	1	L	254.1	260.2	8.0	42.6
P233	1	T	255.6	268.5	7.0	35.5
P234	1	T	258.8	269.8	6.0	31.5
P211	3*	L	266.9	274.8	8.0	47.9
P212	3*	L	264.9	274.1	8.0	45.8
P235	3*	T	274.2	284.9	6.5	30.9
P236	3*	T	273.0	284.5	6.0	33.2
P213	6	L	274.3	282.6	8.0	46.4
P214	6	L	270.5	279.8	7.5	42.1
P237	6	T	278.5	289.9	5.0	33.9
P238	6	T	275.7	285.9	4.5	29.9
P215	12	L	277.2	285.9	6.0	44.4
P216	12	L	275.7	283.6	8.0	46.3
P239	12	T	265.0	275.5	6.0	33.3
P240	12	T	263.3	277.7	6.5	40.2

NOTES:

1. L = Longitudinal; T = Transverse

2. All results obtained with 0.505" diameter specimens

3. *3 Hour specimens inadvertently aged at 915°F

APPENDIX IV (Cont'd.) - PLATE TENSILE DATA SUMMARY

UNIAXIAL TENSILE DATA - HEATS-A AND B PLATE AGED AT 900°F

HEAT-A PLATE

SPEC. NO.	TIME AT TEMPERATURE (HOURS)	SPECIMEN ORIENTATION	0.2% YIELD STRESS (KSI)	ULTIMATE STRESS (KSI)	% ELONG. (IN 2") GAGE	% RED. IN AREA
AP29	1	L	243.2	249.9	10.0	45.2
AP210	1	L	240.0	249.9	10.0	45.5
AP233	1	T	239.2	249.9	8.0	34.0
AP234	1	T	242.3	250.6	9.0	36.6
AP211	3	L	255.2	261.6	10.5	42.2
AP212	3	L	255.0	261.6	8.0	37.6
AP235	3	T	252.2	262.9	8.0	32.7
AP236	3	T	256.0	261.8	7.0	32.0
AP213	6	L	260.3	265.7	9.0	39.1
AP214	6	L	259.8	265.4	10.0	42.8
AP237	6	T	260.8	267.4	8.0	34.4
AP238	6	T	259.1	267.0	8.0	35.3
AP215	12	L	261.8	268.2	10.0	43.5
AP216	12	L	259.8	266.4	9.0	39.0
AP239	12	T	260.9	268.5	6.5	34.4
AP240	12	T	261.9	268.4	7.0	37.0

HEAT-B PLATE

SPEC. NO.	TIME AT TEMPERATURE (HOURS)	SPECIMEN ORIENTATION	0.2% YIELD STRESS (KSI)	ULTIMATE STRESS (KSI)	% ELONG. (IN 2") GAGE	% RED. IN AREA
P217	1	L	261.8	269.5	11.0	49.4
P218	1	L	264.4	268.7	9.0	43.6
P241	1	T	252.6	266.2	9.0	41.5
P242	1	T	254.1	266.4	9.5	42.1
P219	3	L	271.3	279.0	10.0	45.4
P220	3	L	266.8	276.6	9.5	46.4
P243	3	T	253.6	266.2	8.5	41.8
P244	3	T	255.6	266.9	8.5	40.8
P221	6	L	265.9	276.7	10.5	45.7
P222	6	L	265.5	275.5	9.0	44.6
P245	6	T	251.6	264.2	8.5	39.7
P246	6	T	252.6	265.0	9.0	41.2
P223	12	L	256.2	266.9	11.5	45.7
P224	12	L	258.5	268.8	11.0	46.6
P247	12	T	238.2	251.3	10.5	42.4
P248	12	T	238.7	253.6	8.5	38.6

NOTES:

1. L = Longitudinal; T = Transverse

2. All results obtained with 0.505" diameter specimens.

UNIAXIAL TENSILE DATA - HEATS-A AND B PLATE AS-RECEIVED AND AGED AT 875°F

HEAT-A PLATE

SPEC. NO.	TIME AT TEMPERATURE (HOURS)	SPECIMEN ORIENTATION	0.2% YIELD STRESS (KSI)	ULTIMATE STRESS (KSI)	% ELONG. (IN 2" GAGE)	% RED. IN AREA
AP21	1	L	240.4	248.8	10.5	47.4
AP22	1	L	238.6	246.5	11.0	48.2
AP225	1	T	236.8	245.5	10.0	39.6
AP226	1	T	234.8	240.0	9.5	40.1
AP23	3	L	250.1	260.9	11.0	44.3
AP24	3	L	254.2	259.9	12.0	51.1
AP227	3	T	248.6	258.3	9.5	40.7
AP228	3	T	250.4	259.8	8.0	36.6
AP25	6	L	254.7	263.4	9.0	43.5
AP26	6	L	259.1	265.7	10.0	39.5
AP229	6	T	249.4	264.7	7.0	35.7
AP230	6	T	255.3	265.3	6.5	36.7
AP27	12	L	265.4	27.15	8.0	37.6
AP28	12	L	264.5	272.5	8.0	37.7
AP231	12	T	264.9	272.0	8.0	32.8
AP232	12	T	261.9	270.7	8.0	29.8

HEAT-B PLATE

SPEC. NO.	TIME AT TEMPERATURE (HOURS)	SPECIMEN ORIENTATION	0.2% YIELD STRESS (KSI)	ULTIMATE STRESS (KSI)	% ELONG. (IN 2" GAGE)	% RED. IN AREA
PXT	as Rec'd.	T	113.9	163.2	13.0	63.3
PXL	as Rec'd.	L	113.9	160.5	13.5	63.0
P21	1	L	245.9	257.2	8.5	42.4
P22	1	L	242.0	254.9	9.5	41.4
P225	1	T	247.2	259.0	8.0	38.4
P226	1	T	244.9	258.7	8.0	38.4
P23	3	L	257.7	269.2	7.5	39.4
P24	3	L	257.2	268.2	8.0	39.3
P227	3	T	261.5	276.8	5.0	28.5
P228	3	T	263.1	274.7	7.5	29.4
P25	6	L	268.5	277.7	6.0	38.9
P26	6	L	267.2	277.7	5.5	37.4
P229	6	T	273.4	283.9	5.5	25.2
P230	6	T	275.3	285.3	5.0	26.5
P27	12	L	283.1	290.9	7.0	37.2
P28	12	L	278.8	287.5	5.0	35.3
P231	12	T	279.5	294.4	5.5	24.7
P232	12	T	286.3	295.4	5.0	29.6

NOTES:

1. L = Longitudinal; T = Transverse

2. All results obtained with 0.505" diameter specimens

APPENDIX V

PLATE FRACTURE TOUGHNESS DATA 48-IN. AND 24-IN. PTC COUPONS

APPENDIX   V

PLANE STRAIN FRACTURE TOUGHNESS DATA

48" × 4" × 3/4" SPECIMENS

HEAT-1 PLATE

SPEC. NO.	AGING TIME 900°F (HRS.)	CRACK LENGTH (IN.)	CRACK DEPTH (IN.)	GROSS FRACTURE STRENGTH (KSI)	NET FRACTURE STRENGTH (KSI)	KIC (KSI √IN.)	0.2% OFFSET YIELD (KSI)
1-13	3	Control		265.8	---	---	260.0
1-11	3	0.125	0.062	264.8	265.8	---	---
1-18	3	0.240	0.110	260.3	262.1	116.8	---
1-9	3	0.300	0.120	247.2	249.7	123.3	---
1-8	3	0.380	0.150	206.6	209.8	114.0	----
1-2	3	0.435	0.165	198.5	202.6	116.6	----
1-12	3	0.490	0.180	183.1	187.7	113.2	----
1-7	3	0.560	0.190	168.1	173.3	109.6	----
1-10	3	0.606	0.205	155.2	160.9	104.9	----
1-17	3	0.730	0.240	147.9	155.9	109.0	----
1-14	3	1.000	0.290	119.4	131.2	100.2	----
1-15	12	Control		273.0	----	----	268.0
1-6	12	0.102	0.059	273.3	273.7	----	----
1-16	12	0.165	0.079	271.5	272.4	101.1	----
1-4	12	0.363	0.153	191.2	194.0	102.8	----
1-3	12	0.655	0.199	139.1	144.6	95.7	----
1-5	12	0.849	0.235	122.9	130.5	94.0	----
1-1	12	0.883	0.285	113.0	121.6	90.5	----

NOTES:

1. All specimens are longitudinal

2. Blank in Kic column indicates non-applicable value

3. Gross fracture stress = failing load divided by gross area

4. Net fracture stress = failing load divided by gross area minus crack area

APPENDIX V (Cont'd)

PLANE STRAIN FRACTURE TOUGHNESS DATA

24" x 3"x 3/4" SPECIMENS

HEAT-A PLATE

SPEC. NO.	ORIENTATION AND AGING TIME AT 900°F (HRS)	CRACK LENGTH (IN.)	CRACK DEPTH (IN.)	GROSS FRACTURE STRESS, (KSI)	NET-FRACTURE STRESS, (KSI)	K_{IC} (KSI $\sqrt{IN.}$)	APPLICABLE 0.2% OFFSET YIELD (KSI)
AP4-1	L-3	0.224	0.104	263.3	265.4	---	254.8
AP4-2	L-3	0.296	0.131	251.5	254.9	125.3	254.8
AP4-3	L-3	0.383	0.173	200.1	204.8	111.2	254.8
AP4-4	T-3	0.246	0.111	243.8	246.1	110.3	254.8
AP4-5	T-3	0.306	0.130	225.1	228.6	112.9	254.8
AP4-6	T-3	0.377	0.152	180.8	184.6	98.7	254.8

NOTES:

1. L = Longitudinal; T = Transverse

2. Specimens aged 3 Hours at 900°F.

3. Blank in K_{IC} column indicates non applicable value

4. Gross fracture stress = failing load divided by uncracked gage area

5. Net-Fracture stress = failing load divided by uncracked gage area minus area of crack.

PLANE STRAIN FRACTURE TOUGHNESS DATA

24" x 3" x 3/4" SPECIMENS

HEAT B PLATE

SPEC. NO.	ORIENTA- TION	AGING TEMP. AND TIME (°F, HRS)	CRACK LENGTH (IN.)	CRACK DEPTH (IN.)	GROSS FRACTURE STRESS (KSI)	NET FRACTURE STRESS (KSI)	K_{IC} (KSI $\sqrt{IN.}$)	APPLICABLE 0.2% YIELD STRESS (KSI)
PII7	L	875 - 12	0.423	0.157	165.0	169.2	93.9	
PI2I	L	875 - 12	0.110	0.048	291.5	293.1	----	
PII4	L	875 - 12	0.212	0.087	230.7	232.3	95.6	
PI24	L	875 - 12	0.300	0.113	198.3	201.0	96.1	
PII5	L	875 - 12	0.256	0.106	219.4	221.9	99.6	
PI20	L	875 - 12	0.149	0.065	283.0	283.9	----	
PII6	L	875 - 12	Control	----	290.2	----	----	274.5
P44	T	875 - 12	0.212	0.085	212.2	2.316	87.3	
PI7	T	875 - 12	0.106	0.050	291.8	292.3	----	
PI4	T	875 - 12	0.290	0.113	176.2	178.3	83.7	
PII3	T	875 - 12	0.145	0.064	261.7	262.5	90.9	
FI2	T	875 - 12	0.368	0.135	173.9	177.0	92.4	
PI8	T	875 - 12	0.231	0.091	200.8	202.3	85.8	
P46	T	875 - 12	Control	----	294.6	----	----	272.5
PII9	L	900 - 3	0.109	0.051	280.3	280.8	84.7	
PI22	L	900 - 3	0.336	0.136	207.4	210.9	107.3	
PI25	L	900 - 3	0.300	0.121	203.2	205.8	99.2	
P41	L	900 - 3	0.254	0.107	229.2	231.4	104.0	
P42	L	900 - 3	0.491	0.176	154.5	159.4	94.2	
PI26	L	900 - 3	Control	----	282.0	----	----	280.3
PI3	T	900 - 3	0.110	0.050	285.4	286.0	86.8	
PI5	T	900 - 3	0.241	0.100	205.8	207.6	90.2	
PI6	T	900 - 3	0.299	0.118	185.3	187.6	89.7	
PI9	T	900 - 3	0.383	0.140	169.8	173.1	92.1	
PII0	T	900 - 3	0.494	0.170	143.6	148.0	87.3	
31WI	T	900*- 3	0.150	0.070	272.7	273.6	96.4	
31W4	T	900*- 3	0.202	0.085	267.9	268.6	109.3	
PII	T	900 - 3	Control	----	288.7	----	----	282.5
P43	L	900 - 12	0.109	0.051	292.4	292.9	89.0	
P51	L	900 - 12	0.250	0.104	196.2	198.0	87.5	
PII8	L	900 - 12	0.302	0.117	185.4	187.7	90.1	
P52	L	900 - 12	0.378	0.141	173.6	177.0	93.9	
P53	L	900 - 12	0.493	0.171	150.3	155.0	91.5	
PI23	L	900 - 12	Control	----	284.3	----	----	277.6
PIII	T	900 - 12	0.113	0.050	289.9	290.4	89.3	
P55	T	900 - 12	0.239	0.098	192.1	193.7	83.4	
PI2	T	900 - 12	0.290	0.114	173.2	175.3	82.2	
31W2	T	900 - 12	0.379	0.127	174.7	177.8	93.3	
31W3	T	900 - 12	0.491	0.172	159.7	164.8	97.3	
31W6	T	900*- 12	Multiple Surface Cracks		211.0	----	----	
31W7	T	900*- 12	Multiple Surface Cracks		221.0	----	----	
P45	T	900 - 12	Control	----	294.8	----	----	288.6

NOTES:

1. L = Longitudinal; T = Transverse

2. Gross Fracture Stress = Failing Load divided by gross area

3. Net Fracture Stress = Failing Load divided by gross area minus crack area

4. * Aged at 910°F

5. Blank in K_{IC} column indicates non applicable value

APPENDIX VI

PLATE FRACTURE TOUGHNESS DATA 8-IN PTC COUPONS

PLANE STRAIN FRACTURE TOUGHNESS DATA

8" × 11/16" × 5/16" SPECIMENS

HEAT-B PLATE

SPEC. NO.	ORIENTATION AND AGING TIME AT 900°F (HRS)	CRACK LENGTH (IN.)	CRACK DEPTH (IN.)	GROSS FRACTURE STRESS (KSI)	NET FRACTURE STRESS (KSI)	GROSS K_{IC} (KSI $\sqrt{IN.}$)	NET K_{IC} (KSI $\sqrt{IN.}$)	APPLICABLE 0.2% YIELD STRENGTH (KSI)
P61	L-3	0.122	0.058	258.5	265.5	82.4	84.9	265.9
P62	L-3	0.207	0.086	210.7	226.1	86.0	92.8	265.9
P63	L-3	0.285	0.105	163.3	184.9	76.5	87.2	265.9
P64	L-3	0.354	0.125	129.9	157.3	66.9	81.6	265.9
P65	L-3	0.443	0.150	107.8	146.2	61.5	84.2	265.9
P66	L-3	0.450	0.151	106.0	145.0	60.9	84.0	265.9
P67	L-12	0.120	0.055	256.6	263.0	80.9	83.1	276.4
P68	L-12	0.207	0.090	170.1	182.9	68.6	74.0	276.4
P69	L-12	0.295	0.107	142.4	162.7	67.3	77.3	276.4
P610	L-12	0.351	0.119	117.4	140.7	59.7	71.9	276.4
P611	L-12	0.454	0.148	94.9	129.6	54.4	74.7	276.4
P612	L-12	0.457	0.146	102.3	139.5	58.7	80.9	276.4
P613	T-3	0.120	0.055	247.2	253.4	77.7	79.8	273.6
P614	T-3	0.215	0.083	190.1	204.1	78.1	84.2	273.6
P615	T-3	0.430	0.130	93.9	121.0	51.7	67.0	273.6
P616	T-3	0.347	0.117	122.4	145.8	61.9	74.2	273.6
P617	T-3	0.458	0.142	101.6	137.5	58.1	79.2	273.6
P618	T-3	0.248	0.101	150.7	169.8	69.9	79.1	273.6
P619	T-12	0.121	0.053	231.6	237.4	72.9	74.9	264.1
P620	T-12	0.210	0.083	172.7	185.1	70.0	75.3	264.1
P621	T-12	0.270	0.103	141.1	158.3	64.2	72.3	264.1
P622	T-12	0.355	0.121	107.5	129.5	54.9	66.5	264.1
P623	T-12	0.445	0.140	97.3	130.7	54.9	74.3	264.1
P624	T-12	0.446	0.143	92.0	123.4	52.2	70.3	264.1
P6P1	SL-3	0.185	0.076	246.6	259.3	96.0	101.6	269.2
P6P2	SL-3	Control		273.5	----	----	----	269.2
P6P3	SL-3	0.134	0.054	273.7	280.5	91.6	94.3	269.2
P6P4	SL-3	*	*	273.7	NA	NA	----	269.2
P6P5	SL-3	0.325	0.119	159.8	185.6	79.5	93.0	269.2
P6P6	SL-3	0.463	0.147	126.0	167.1	72.7	97.3	269.2

NOTES:

1. All results obtained with 5/16" × 11/16" × 8" slab specimens

2. L = Longitudinal; T = Transverse; S = surface type specimen

3. Gross Fracture Stress = Failing load divided by gross area

4. Net Fracture Stress = Failing load divided by gross area minus crack area

5. 3 Hours specimens inadvertently aged at 915°F

6. * Failed away from crack

APPENDIX VII

WELDMENT TENSILE DATA W9 WELDS

TYPE W9 WELDS IN HEAT-B PLATE

SPEC. NO.	CONDITION OF PLATE PRIOR TO WELDING	ORIENTA-TION	AGING TEMP., (°F)	AGING TIME (HRS)	0.2% YIELD STRENGTH (KSI)	ULTIMATE STRENGTH (KSI)	% ELONG (1" or 2" GAGE)	% RED IN AREA	REMARKS
21AA1	As Rec'd.	L-AWM	875	1.5	223.5	240.6	8.0	22.3	
21BB1	As Rec'd.	L-AWM	875	3.0	231.0	247.3	6.0	16.8	
21CC1	As Rec'd.	L-AWM	875	6.0	250.7	256.3	1.0	2.5	G
21DD1	As Rec'd.	L-AWM	875	12.0	255.1	268.0	1.0	4.1	G
21GG1	Aged	L-AWM	875	1.5	217.6	234.5	8.5	29.6	H
21HH1	Aged	L-AWM	875	3.0	224.4	239.7	6.0	22.8	H
21JJ1	Aged	L-AWM	875	6.0	254.5	263.3	1.0	3.1	G
21KK1	Aged	L-AWM	875	12.0	260.8	276.2	2.0	3.2	G
21AA2	As Rec'd.	T	875	1.5	222.8	243.0	6.0	23.8	B,C
21BB2	As Rec'd.	T	875	3.0	236.1	246.4	BOGM	37.3	B,C
21CC2	As Rec'd.	T	875	6.0	235.3	250.3	4.5	30.0	B,C
21DD2	As Rec'd.	T	875	12.0	251.7	256.1	2.0	39.3	B,C
21GG2	Aged	T	875	1.5	223.9	242.0	1.0	3.2	A,F
21HH2	Aged	T	875	3.0	232.4	247.2	7.0	47.0	B,C
21JJ2	Aged	T	875	6.0	248.2	259.4	6.5	37.0	B,C
21GG6	Aged	T	875	12.0	242.0	251.3	BOGM	26.2	B,C
21AA3	As Rec'd.	L-AWM	900	1.5	232.4	247.7	1.0	5.5	G,H
21BB3	As Rec'd.	L-AWM	900	3.0	240.8	258.7	4.5	18.3	G,H
21CC3	As Rec'd.	L-AWM	900	6.0	257.4	257.4	1.0	6.3	G
21DD3	As Rec'd.	L-AWM	900	12.0	NA	249.3	BOGM	1.6	H
21GG3	Aged	L-AWM	900	1.5	225.7	241.1	6.0	24.6	
21HH3	Aged	L-AWM	900	3.0	240.1	249.3	1.0	1.6	G
21JJ3	Aged	L-AWM	900	6.0	261.7	274.1	3.0	6.3	G
21KK3	Aged	L-AWM	900	12.0	261.8	275.6	1.0	3.3	G
21AA4	As Rec'd.	T	900	1.5	224.2	242.5	4.5	27.7	B
21BB4	As Rec'd.	T	900	3.0	235.0	244.9	BOGM	34.7	B,C
21CC4	As Rec'd.	T	900	6.0	235.2	246.7	4.5	32.8	B
21DD4	As Rec'd.	T	900	12.0	236.4	246.4	4.5	27.1	B,H
21GG4	Aged	T	900	1.5	226.4	242.8	5.0	31.9	B,H
21HH4	Aged	T	900	3.0	229.0	244.4	4.0	40.8	B
21JJ4	Aged	T	900	6.0	246.2	225.1	6.0	41.4	B
21JJ6	Aged	T	900	12.0	NA	213.3	0.5	3.2	A,K
21AA5	As Rec'd.	L-AWM	950	1.5	268.7	274.7	4.0	6.3	G
21BB5	As Rec'd.	L-AWM	950	3.0	268.1	282.4	2.0	9.7	G
21CC5	As Rec'd.	L-AWM	950	6.0	NA	265.6	1.0	3.1	G
21DD5	As Rec'd.	L-AWM	950	12.0	265.3	276.0	1.0	0.8	G
21GG5	Aged	L-AWM	950	1.5	253.9	268.6	4.0	14.1	H
21HH5	Aged	L-AWM	950	3.0	262.2	273.5	1.0	2.3	G
21JJ5	Aged	L-AWM	950	6.0	254.6	273.5	3.0	10.9	G
21KK5	Aged	L-AWM	950	12.0	266.5	269.8	1.0	3.3	G
21AA6	As Rec'd.	T	950	1.5	232.3	249.2	3.0	26.5	B
21BB6	As Rec'd.	T	950	3.0	NA	221.1	0	1.9	A,E
21CC6	As Rec'd.	T	950	6.0	238.5	245.7	3.0	13.2	B,K
21DD6	As Rec'd.	T	950	12.0	221.6	233.8	5.5	38.8	B
21KK2	Aged.	T	950	1.5	NA	230.0	3.0	24.3	B,K
21HH6	Aged	T	950	3.0	244.3	253.1	3.5	38.1	B
21KK4	Aged	T	950	6.0	239.5	247.4	3.0	13.1	B
21KK6	Aged	T	950	12.0	NA	182.3	0	0.4	A,G
7B2	As Rec'd.	T		As Welded	131.0	152.7	2.0	14.0	A
7B1	As Rec'd.	T		As Welded	132.0	150.1	2.0	13.6	A
4A31	As Rec'd.	L-AWM		As Welded	141.8	151.9	6.0	52.1	

NOTES:

1. L-AWM - Longitudinal all-weldmetal specimen; 0.250-in. diam., 1-in. gage.
2. T - Transverse across-the-joint specimen; 0.505-in. diam., 2-in. gage.
3. See Table XIII for definition of Remark codes.
4. BOGM - Broke outside gage mark
5. NA - not available
6. Plates aged prior to welding were aged at 900°F for 3 hours.

APPENDIX VIII

WELDMENT TENSILE DATA W7 AND W8 WELDS

APPENDIX VIII - WELDMENT TENSILE DATA SUMMARY

TYPE-W7 WELDS IN HEAT-P PLATE

SPEC. NO.	AGING TEMP., (°F)	AGING TIME (HOURS)	ORIENTATION AND TYPE	0.2% YIELD STRENGTH (KSI)	ULTIMATE STRENGTH (KSI)	% ELONG (1" OR 2" GAGE)	% RED IN AREA	REMARKS
7A2	875	1.5	L-AWM	215.2	237.4	9.0	32.7	
7A6	875	3.0	L-AWM	220.9	238.7	8.5	38.1	
7A7	875	6.0	L-AWM	236.4	253.5	7.5	26.1	
7C10	875	12.0	L-AWM	249.5	264.7	6.5	32.7	
7A3	900	1.5	L-AWM	225.1	239.3	9.0	36.0	
7A5	900	3.0	L-AWM	230.5	247.8	8.5	37.7	
7A9	900	6.0	L-AWM	242.4	260.1	5.5	25.3	
7C11	900	12.0	L-AWM	251.5	266.7	3.0	11.7	
4A32	900	12.0	L-AWM	266.4	272.3	7.0	29.0	
7A1	950	1.5	L-AWM	236.6	254.5	8.5	37.6	
7A4	950	3.0	L-AWM	249.5	265.4	7.0	30.7	
7A8	950	6.0	L-AWM	251.5	267.2	5.0	19.0	
7C12	950	12.0	L-AWM	252.6	269.4	6.0	30.1	
7A15	900	3.0	T	246.7	256.4	2.0	10.1	D
7A19	900	6.0	T	254.4	268.4	4.0	16.0	D
7A23	900	12.0	T	259.2	271.8	4.0	25.4	B
7A13	950	3.0	T	256.0	266.0	4.5	26.8	B
7A17	950	6.0	T	252.1	263.6	3.5	35.2	B
7A21	950	12.0	T	249.5	260.5	4.5	28.5	B

NOTES:

1. L-AWM - Longitudinal all weldmetal specimen (0.250-in. diam.); 1-in. gage.

2. T = Transverse across-the-joint specimen (0.505-in diam.); 2-in. gage

3. For definition of remark codes see Table XIII .

APPENDIX VIII (Cont'd.), WELDMENT TENSILE DATA SUMMARY

TYPE - W8 WELDS IN HEAT-B PLATE

SPEC. NO.	CONDITION OF PLATE PRIOR TO WELDING	AGING TEMP. (°F)	AGING TIME (HRS)	ORIENTATION AND TYPE	0.2% YIELD STRENGTH (KSI)	ULTIMATE STRENGTH (KSI)	% ELONG. (1" or 2" GAGE)	% RED IN AREA	REMARKS
211A1	As Rec'd.	875	1.0	L-AWM	206.0	224.0	6.0	26.5	
211B1	As Rec'd.	875	2.5	L-AWM	220.0	236.0	4.0	10.1	
211C1A	As Rec'd.	875	5.5	L-AWM	248.0	260.0	3.0	12.4	
211C1B	As Rec'd.	875	5.5	L-AWM	241.0	256.0	7.0	31.1	
211D1	As Rec'd.	875	11.5	L-AWM	262.0	274.0	4.0	20.3	
211G1	Aged	875	1.0	L-AWM	190.0	212.0	7.0	25.9	
211H1	Aged	875	2.5	L-AWM	200.0	230.0	4.0	27.2	
211J1	Aged	875	5.5	L-AWM	248.0	260.0	7.0	29.2	
211K1	Aged	875	11.5	L-AWM	252.0	266.0	5.0	17.9	
211A2	As Rec'd.	875	1.0	T	203.0	225.0	8.0	33.3	B
211B2	As Rec'd.	875	2.5	T	206.0	221.0	7.0	36.6	B
211C2	As Rec'd.	875	5.5	T	219.0	237.0	5.0	28.2	B
211D2	As Rec'd.	875	11.5	T	224.0	243.0	5.0	28.8	B
211G2	Aged	875	1.0	T	208.0	220.0	7.0	36.3	A
211H2	Aged	875	2.5	T	216.0	227.0	8.0	38.5	B
211J2	Aged	875	5.5	T	234.0	243.5	4.0	20.6	C
211K2	Aged	875	11.5	T	236.0	244.5	3.0	16.3	C
211A3	As Rec'd.	900	1.0	L-AWM	234.0	248.0	8.0	37.0	
211B3A	As Rec'd.	900	2.5	L-AWM	261.0	265.0	4.0	7.9	
211B3B	As Rec'd.	900	2.5	L-AWM	234.0	222.0	5.0	20.2	
211C3	As Rec'd.	900	5.5	L-AWM	254.0	266.0	6.0	35.9	
211D3	As Rec'd.	900	11.5	L-AWM	255.0	276.0	5.0	18.5	
211G3	Aged	900	1.0	L-AWM	230.0	238.0	7.0	34.5	
211H3	Aged	900	2.5	L-AWM	230.0	246.0	7.0	33.9	
211J3	Aged	900	5.5	L-AWM	252.0	264.0	5.0	31.3	
211K3	Aged	900	11.5	L-AWM	264.0	274.0	5.0	27.9	
211A4A	As Rec'd.	900	1.0	T	220.0	235.0	5.0	27.0	B
211A4B	As Rec'd.	900	1.0	T	218.0	237.0	5.0	25.8	B
211B4	As Rec'd.	900	2.5	T	207.0	222.0	5.0	20.2	B
211C4	As Rec'd.	900	5.5	T	222.5	241.0	4.0	22.3	B
211D4	As Rec'd.	900	11.5	T	227.0	242.0	5.0	28.2	B
211G4	Aged	900	1.0	T	225.0	236.0	10.0	40.7	C
211H4	Aged	900	2.5	T	222.0	234.0	6.0	34.5	B
211J4	Aged	900	5.5	T	234.0	245.5	4.0	23.7	B
211K4	Aged	900	11.5	T	236.0	243.5	3.0	14.1	C
211A5	As Rec'd.	950	1.0	L-AWM	252.0	267.0	6.0	31.0	
211B5	As Rec'd.	950	2.5	L-AWM	232.0	256.0	5.0	25.6	
211C5	As Rec'd.	950	5.5	L-AWM	262.0	276.0	4.0	23.6	
211D5	As Rec'd.	950	11.5	L-AWM	250.0	262.0	3.0	16.7	
211G5	Aged	950	1.0	L-AWM	230.0	248.0	7.0	36.4	
211H5	Aged	950	2.5	L-AWM	250.0	262.0	3.0	13.8	
211J5	Aged	950	5.5	L-AWM	252.0	270.0	5.0	14.5	
211K5	Aged	950	11.5	L-AWM	244.0	264.0	5.0	17.5	
211A6	As Rec'd.	950	1.0	T	225.0	237.0	4.0	18.4	C
211B6	As Rec'd.	950	2.5	T	219.0	236.0	4.0	17.8	B
211C6	As Rec'd.	950	5.5	T	217.0	234.0	6.0	30.0	D
211D6	As Rec'd.	950	11.5	T	215.0	230.5	7.0	37.9	D
211G6	Aged	950	1.0	T	233.0	243.0	5.0	22.1	C
211H6	Aged	950	2.5	T	223.0	230.0	5.0	23.4	C
211J6	Aged	950	5.5	T	222.0	234.5	5.0	28.5	D
211K6	Aged	950	11.5	T	217.5	228.0	2.0	11.5	C

NOTES:

1. L-AWM - Longitudinal all weldmetal specimen; 0.250-in. diam, 1-in. gage.
2. T - transverse across-the-joint specimen; 0.505-in. diam, 2-in. gage.
3. See Table XIII for definition of Remark codes
4. Plates aged prior to welding were aged at 900°F for 3 hours.

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APPENDIX IX

WELDMETAL FRACTURE TOUGHNESS DATA

APPENDIX IX – DATA SUMMARY HEAT I PLATE WELDS - FRACTURE TOUGHNESS

Spec. No.	Aging Time (Hours)	Aging Temp. (°F)	Crack Length (Inches)	Crack Depth (Inches)	Gross Fracture Stress (KSI)	Net Fracture Stress (KSI)	Gross K_{Ic} (KSI√in)	Net K_{Ic} (KSI√in)	Applicable 0.2% Yield Stress (KSI)	Weld Type
24" x 3" x 3/4" Welds										
1A-1	3.0	900	0.041	0.019	266.3	266.4	NA	NA		W2
1A-2	3.0	900	Control		246.0	246.0	NA	NA	238.0	W2
1A-3	3.0	900	0.265	0.118	107.7	108.8	42.5	NA		W2
1A-4	3.0	900	0.220	0.105	112.3	113.1	46.5	NA		W2
1A-5	3.0	900	0.147	0.065	147.3	147.7	50.1	NA		W2
1A-6	3.0	900	0.064	0.035	250.0	250.1	NA	NA		W2
8" x 1/2" x 1/8"										
1A2-2	3.0	900	0.081	0.035	233.8	242.6	60.8	63.4	237.0	
(1A6-2)	3.0	900	0.050*	---	256.7	---	NA	NA		W2
(1A2-3)	3.0	900	0.050*	---	252.6	---	NA	NA		W2
1A6-3	3.0	900	0.085	0.035	229.1	238.1	NA	NA		W2
1A2-4	3.0	900	0.134	0.050	177.3	193.8	57.6	63.4	237.0	W2
(1A6-4)	3.0	900	0.134	0.045	209.3	228.3	67.9	74.8	237.0	W2
1A2-10	3.0	900	0.219	0.063	165.9	205.5	66.2	83.7	237.0	W2
(1A6-10)	3.0	900	0.214	0.063	124.0	153.2	48.3	60.3	237.0	W2
1A2-1	3.0	900	0.135	0.049	184.1	202.7				W2
(1A2-3)	3.0	900	0.137	0.053	170.0	187.8				W2
(1A2-4)	3.0	900	0.217	0.063	110.7	138.2				W2
5-3-B	3.0	900	Control		241.7	---	NA	NA		W3
5-3-H	3.0	900	0.030*	---	243.5	---	NA	NA		W3
5-3-D	3.0	900	0.030*	---	243.4	---	NA	NA		W3
5-3-E	3.0	900	0.104	0.060	199.4	217.6				W3
5-3-F	3.0	900	0.123	0.048	211.9	229.1				W3
5-3-G	3.0	900	0.147	0.057	205.2	229.7				W3
5-16-3	3.0	900	0.122	0.045	226.0	244.4				W4
5-16-4	3.0	900	0.095	0.037	240.3	252.2				W4
5-16-5	3.0	900	0.104	0.046	238.7	254.8				W4
5-16-6	3.0	900	0.115	0.046	224.1	241.3				W4
5-16-7	3.0	900	0.152	0.055	176.2	199.1				W4
5-80	12.0	900	Control		250.8	---	NA	NA		W1
5-80-A	12.0	900	0.180	0.057	149.6	172.3				W1
5-80-B	12.0	900	0.187	0.059	141.9	165.1				W1
1A2-5	12.0	900	Control		269.8	---	NA	NA		W2
1A6-5	12.0	900	Control		247.3	---	NA	NA		W2
1A2-6	12.0	900	0.050*	---	247.1	---	NA	NA		W2
(1A6-6)	12.0	900	0.050*	---	268.7	---	NA	NA		W2
(1A2-7)	12.0	900	0.080	0.032	207.0	213.0				W2
1A6-7	12.0	900	0.070	0.032	238.2	244.9				W2
1A2-8	12.0	900	0.132	0.045	168.8	183.1				W2
(1A6-8)	12.0	900	0.139	0.045	131.5	143.8				W2
(1A2-9)	12.0	900	0.214	0.059	108.7	132.4				W2
1A6-9	12.0	900	0.190	0.060	113.8	134.7				W2
(1A6-11)	12.0	900	0.202	0.059	110.5	131.7				W2
5-1-1	12.0	900	Control		237.2	---	NA	NA		W6
5-1-2	12.0	900	0.030	0.015	239.1	240.5				W6
5-1-3	12.0	900	0.080	0.036	204.5	212.3				W6
5-1-4	12.0	900	0.230	0.070	105.3	134.4				W6
5-1-5	12.0	900	0.125	0.046	161.5	174.6				W6
5-1-6	12.0	900	0.203	0.062	119.6	143.9				W6

NOTES:

1. Specimen numbers in parenthesis indicate a resolution heat treat (1500°F 1 hr.) before aging.

2. * Did not fail at crack.

3. NA not applicable

4. Blank in K_{Ic} columns indicate that K_{Ic} was not determined.

5. See Table XI for definition of weld type.

6. Gross fracture stress = failing load divided by gross area.

7. Net fracture stress = failing load divided by gross area minus crack area.

APPENDIX IX (Cont'd.), EFFECT OF AGING TIME AND TEMPERATURE ON FRACTURE TOUGHNESS

PROPERTIES OF TYPE W7 AND W8 WELDMETAL - TRANSVERSE THICKNESS TYPE

8" x 11/16" x 5/16"

SPEC. NO.	AGING TIME (HOURS)	AGING TEMP. (°F)	CRACK LENGTH (INCHES)	CRACK DEPTH (INCHES)	GROSS FRACTURE STRESS (KSI)	NET FRACTURE STRESS (KSI)	GROSS KIC (KSI √IN)	NET KIC (KSI √IN)	APPLICABLE 0.2% YIELD STRENGTH (KSI)	WELD TYPE
214D1	1.5	875	0.050*	---	239.1	---	---	---	204.0	W8
214E1	1.5	875	0.137	0.065	196.4	202.9	66.2	68.7	204.0	W8
214F1	1.5	875	0.252	0.095	152.8	167.6	67.9	75.5	204.0	W8
4J9	1.5	875	0.194	0.083	153.5	163.0	60.4	64.4	204.0	W7
2A9	1.5	875	0.142	0.064	178.5	184.5	60.8	63.0	204.0	W7
4F3	1.5	875	0.050*	---	239.1	---	----	----	204.0	W7
214H1	3.0	875	0.062	0.029	240.5	242.1	----	----	214.0	W8
214J1	3.0	875	0.122	0.053	198.3	203.2	62.9	64.7	214.0	W8
214D2	3.0	875	0.247	0.091	142.6	155.5	61.7	68.7	214.0	W8
4J1	3.0	875	0.065	0.031	253.2	255.0	----	----	214.0	W7
2A1	3.0	875	0.119	0.053	201.0	205.6	63.1	64.7	214.0	W7
4H1	3.0	875	0.295	0.110	113.2	128.1	53.5	60.9	214.0	W7
214F2	6.0	875	0.050*	---	250.2	---	----	----	242.0	W8
214G2	6.0	875	0.134	0.063	151.6	156.6	49.4	51.1	242.0	W8
214H2	6.0	875	0.289	0.114	102.7	117.4	48.1	54.8	242.0	W8
4J2	6.0	875	0.108	0.049	190.9	194.6	56.5	57.7	242.0	W7
2A2	6.0	875	0.175	0.076	146.3	153.7	54.3	57.2	242.0	W7
4H2	6.0	875	0.050*	---	257.4	---	----	----	242.0	W7
214D3	12.0	875	0.050*	---	256.2	---	----	----	255.0	W8
214E3	12.0	875	0.124	0.051	185.4	189.8	58.3	60.1	255.0	W8
214F3	12.0	875	0.188	0.078	128.2	135.6	49.0	52.0	255.0	W8
4J11	12.0	875	0.106	0.048	205.4	209.2	60.6	61.8	255.0	W7
2A11	12.0	875	0.111	0.048	198.7	202.6	59.8	61.1	255.0	W7
4F5	12.0	875	0.280	0.101	111.6	124.2	51.1	57.0	255.0	W7
214H3	1.5	900	0.058	0.026	239.5	240.9	----	----	230.0	W8
214J3	1.5	900	0.159	0.064	185.2	193.1	66.0	69.0	230.0	W8
214D4	1.5	900	0.289	0.100	120.7	135.0	55.8	62.7	230.0	W8
4J3	1.5	900	0.106	0.054	196.0	200.1	59.5	60.9	230.0	W7
2A3	1.5	900	0.204	0.082	190.0	202.2	76.8	82.0	230.0	W7
4H3	1.5	900	0.050*	---	244.8	---	----	----	230.0	W7
214F4	3.0	900	0.050*	---	251.5	---	----	----	232.0	W8
214G4	3.0	900	0.115	0.044	192.1	195.8	58.0	59.2	232.0	W8
214H4	3.0	900	0.224	0.088	136.6	147.1	56.7	61.2	232.0	W8
4J4	3.0	900	0.052*	---	256.5	---	----	----	232.0	W7
2A4	3.0	900	0.119	0.055	203.1	208.0	63.1	64.8	232.0	W7
4H4	3.0	900	0.220	0.079	161.0	171.6	66.0	70.6	232.0	W7
214D5	6.0	900	0.050*	---	251.3	---	----	----	249.0	W8
214E5	6.0	900	0.120	0.057	178.4	182.9	55.2	56.7	249.0	W8
214F5	6.0	900	0.248	0.098	121.7	133.5	53.0	58.6	249.0	W8
4J12	6.0	900	0.110	0.048	227.6	232.0	68.4	69.9	249.0	W7
2A12	6.0	900	0.210	0.080	139.5	148.5	55.9	59.6	249.0	W7
4F6	6.0	900	0.053*	---	259.2	---	----	----	249.0	W7
214H5	12.0	900	0.050*	---	253.4	---	----	----	259.0	W8
214J5	12.0	900	0.115	0.050	178.2	182.1	53.8	55.1	259.0	W8
214D6	12.0	900	0.207	0.080	136.3	145.6	54.2	58.3	259.0	W8
4J5	12.0	900	0.050*	---	262.8	---	----	----	259.0	W7
2A5	12.0	900	0.118	0.047	179.5	183.2	54.9	55.9	259.0	W7
4H5	12.0	900	0.230	0.079	120.4	128.8	49.5	53.1	259.0	W7
214F6	1.5	950	0.050*	---	247.1	---	----	----	240.0	W8
214G6	1.5	950	0.132	0.056	182.7	187.7	59.3	61.0	240.0	W8
214H6	1.5	950	0.262	0.097	123.2	136.3	54.8	60.8	240.0	W8
4J6	1.5	950	0.107	0.046	216.5	220.4	64.0	65.2	240.0	W7
2A6	1.5	950	0.215	0.077	139.8	148.7	56.3	60.0	240.0	W7
4H6	1.5	950	0.052*	---	251.8	---	----	----	240.0	W7
214D7	3.0	950	0.050*	---	248.9	---	----	----	244.0	W8
214E7	3.0	950	0.112	0.049	199.1	203.2	59.8	61.1	244.0	W8
214F7	3.0	950	0.200	0.082	127.3	135.4	50.1	53.4	244.0	W8
4J10	3.0	950	0.050*	---	259.1	---	----	----	244.0	W7
2A10	3.0	950	0.111	0.048	215.2	219.4	64.0	66.0	244.0	W7
4F4	3.0	950	0.295	0.105	104.4	117.5	48.7	52.1	244.0	W7

APPENDIX IV (Cont'd.), EFFECT OF AGING TIME AND TEMPERATURE ON FRACTURE TOUGHNESS

PROPERTIES OF TYPE W7 AND W8 WELDMETAL - TRANSVERSE THICKNESS TYPE

8" x 11/16" x 5/16" (Cont'd.)

SPEC. NO.	AGING TIME (HOURS)	AGING TEMP. (°F)	CRACK LENGTH (INCHES)	CRACK DEPTH (INCHES)	GROSS FRACTURE STRESS (KSI)	NET FRACTURE STRESS (KSI)	GROSS KIC (KSI $\sqrt{IN}$)	NET KIC (KSI $\sqrt{IN}$)	APPLICABLE 0.2% YIELD STRENGTH (KSI)	WELD TYPE
214H7	6.0	950	0.050*	---	247.9	---	---	---	255.0	W8
214J7	6.0	950	0.124	0.050	220.8	226.0	70.1	71.9	255.0	W8
214D8	6.0	950	0.251	0.091	130.5	142.5	56.7	62.1	255.0	W8
4J7	6.0	950	0.194	0.074	131.5	138.6	50.5	50.5	255.0	W7
2A7	6.0	950	0.108	0.045	217.3	221.2	64.4	65.7	255.0	W7
4F1	6.0	950	0.050*	---	254.8	---	---	---	255.0	W7
214F8	12.0	950	0.050*	---	241.8	---	---	---	249.0	W8
214G8	12.0	950	0.115	0.050	194.3	198.5	59.1	60.5	249.0	W8
214H8	12.0	950	0.199	0.081	126.9	134.8	49.7	53.0	249.0	W8
4J8	12.0	950	0.050*	---	254.9	---	---	---	249.0	W7
2A8	12.0	950	0.113	0.048	179.1	182.7	53.7	54.8	249.0	W7
4F2	12.0	950	0.286	0.103	110.9	124.1	51.2	57.4	249.0	W7

NOTES:

1. * Did not fail at crack

2. Dash indicates non-applicable value

3. See Table   for definition of weld types.

4. Gross fracture stress = Failing load divided by gross area.

5. Net fracture stress = Failing load divided by gross area minus crack area.

APPENDIX IX, (Cont'd.), WELDMETAL FRACTURE TOUGHNESS DATA - TYPES W7 AND W8 WELDS - LONGITUDINAL

ALLWELDMETAL 8" x 5/16" x 11/16" SPECIMENS AGED AT 900°F FOR 3 HOURS

SPEC. NO.	WELD TYPE	CRACK LENGTH (IN.)	CRACK DEPTH (IN.)	GROSS FRACTURE STRESS (KSI)	NET FRACTURE STRESS (KSI)	GROSS KIC (KSI √IN)	NET KIC (KSI √IN)	APPLICABLE 0.2% YIELD STRESS (KSI)
213DI	W8	0.090	0.040	206.4	212.4	61.3	62.8	230.5
213EI	W8	0.044	0.019	253.9	255.6	49.3	49.7	230.5
213GI	W8	0.151	0.054	179.9	192.8	61.8	66.6	230.5
213HI	W8	0.202	0.066	138.7	156.0	53.5	60.5	230.5
213JI	W8	0.305	0.079	109.8	138.7	48.9	62.0	230.5
2A31	W7	0.215	0.074	136.8	152.4	55.1	61.5	230.5
4E31	W7	0.150	0.059	168.3	178.1	57.9	61.5	230.5
4F31	W7	0.094	0.043	229.6	235.3	64.5	66.2	230.5
4G31	W7	0.044	0.023	253.5	255.0	51.5	51.9	230.5
4J31	W7	0.321	0.091	106.7	132.0	49.8	62.2	230.5

NOTES:

1. Gross fracture stress = Ultimate load divided by gross area

2. Net fracture stress = Ultimate load divided by gross area minus crack area.

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APPENDIX X

HEAT-AFFECTED ZONE FRACTURE TOUGHNESS DATA

APPENDIX X (Cont'd.), HEAT-AFFECTED ZONE FRACTURE TOUGHNESS DATA - TYPE W7 WELDS - TRANSVERSE

THICKNESS TYPE 8" × 11/16" × 5/16" PTC SPECIMENS AGED AT 900°F FOR 3 HOURS

SPEC. NO.	PLATE CONDITION PRIOR TO WELDING	CRACK LENGTH (IN.)	CRACK DEPTH (IN.)	GROSS FRACTURE STRESS (KSI)	NET FRACTURE STRESS (KSI)	GROSS K_{IC} (KSI $\sqrt{IN}$)	NET K_{IC} (KSI $\sqrt{IN}$)	APPLICABLE 0.2% YIELD (KSI)
4A1	Aged	0.254	0.099	188.0	207.5	88.4	97.8	246.6
4A3	Aged	0.112	0.052	249.6	254.9	NA	---	246.6
4A5	Aged	0.050*	----	262.5	262.5	---	---	246.6
4A7	Aged	0.195	0.083	202.6	215.1	80.5	85.8	246.6
4F7	As Rec'd.	0.055	0.024	252.8	254.0	NA	---	246.6
4F8	As Rec'd.	0.256	0.103	174.3	192.5	66.8	86.8	246.6
4F9	As Rec'd.	0.105	0.050	248.2	253.0	NA	---	246.6
4F10	As Rec'd.	0.175**	0.094	145.3	154.4	NA	---	246.6

NOTES:

1. * Failed away from installed notch.

2. ** Failed away from installed notch. The crack diemnsions invalidate K_{IC}.

3. The plane of the partial thickness crack was oriented perpendicular to the plate rolling direction.

4. Plate aged prior to welding was aged at 900°F for 3 hours.

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